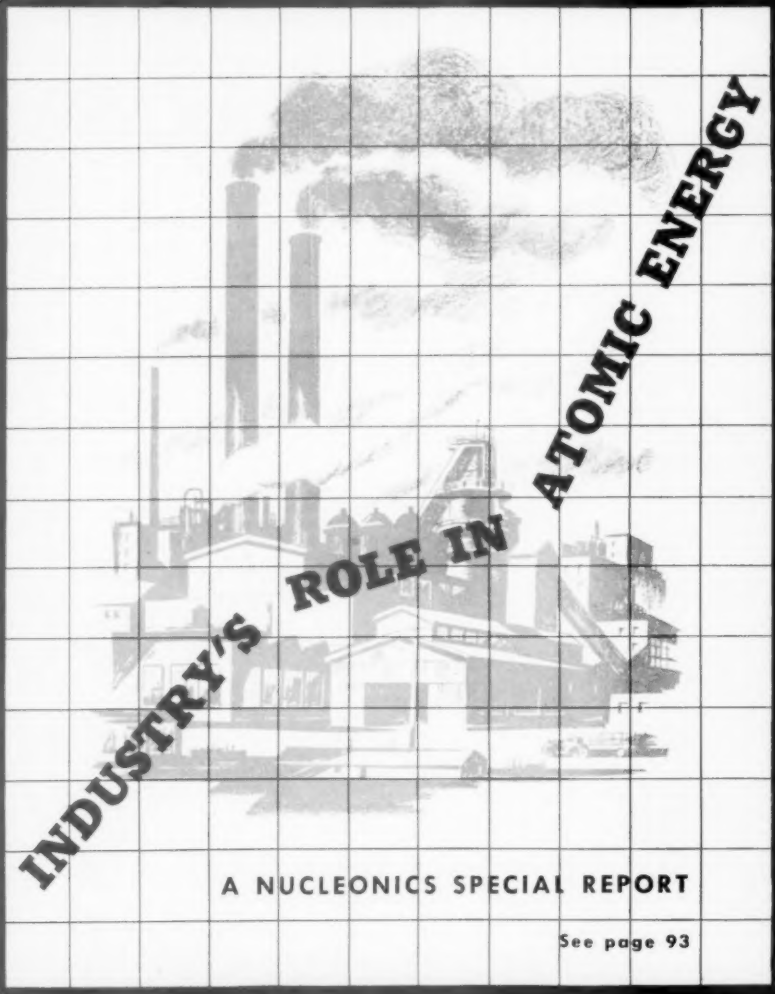
NUCLEONICS



INDUSTRY'S ROLE IN ATOMIC ENERGY

A NUCLEONICS SPECIAL REPORT

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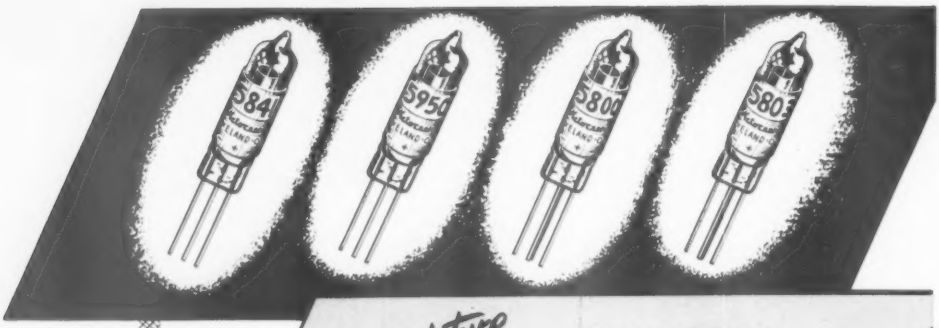
A McGRAW-HILL PUBLICATION ★ SEVENTY-FIVE CENTS



Subminiature VICTOREEN ELECTRON TUBES

VERSATILE

VACUUM TUBES

The Victoreen Sub-Miniature 10 Milliampere Filament Series Vacuum Tubes were designed specifically to give the ultimate in stable performance consistent with very small physical size and absolute minimum filament drain. They were originally intended for use in extremely compact, portable, battery-operated equipment, and in this field they are unsurpassed. It was very quickly discovered, however, that their unique properties also made them extremely useful in the design of line-operated and stationary equipment.

The 5886 pentode and the 5800 tetrode are sub-miniature electrometer tubes having high emission stability and low microphonics. In these tubes the amplification factor is high enough to afford substantial voltage gain in the electrometer stage of multi-stage circuits requiring the ultimate in low grid currents.

The 5803 and, the 5886 triode connected, have unusually high ratios of transconductance to control grid current in single stage circuits for portable application where low input grid current with maximum gain per stage is necessary.

The 5799 is a high vacuum rectifier with an inverse peak voltage rating which makes this tube ideally suited for use in high voltage low current portable equipment power supplies where low power consumption and compactness are required. Its low leakage and high back resistance make it suitable for measuring apparatus requiring the ultimate in high input impedance.

MANY TYPES

VOLTAGE REGULATOR TUBES

The need for low current sub-miniature type voltage regulators was acknowledged by Victoreen and led to an extensive series of corona regulators and negative glow discharge tubes. General use has shown major applications for these tubes in high voltage stabilization, high voltage peak limiting and high voltage reference circuits. Corona regulators at present cover a wide range of operating voltage points in the region of 500 to 2500 volts.

The 5950, 5841 and 6143 were specifically designed for voltage regulation points at **700, 900** and **1200** Volts center plateau operating points for commercially available geiger and photo-multiplier tubes.

The VXR-500, VXR-1000, VXR-1500 and 6119 furnish convenient reference points at **500, 1000, 1500,** and **2000** volts.

The type VXR-130 sub-miniature negative glow regulator was specifically designed for portable "B" supply operation. Its close regulation, however, widens the applications possible to any which require voltage reference.

RIGID SPECIFICATIONS

COUNTER TUBES

The Victoreen Thyrodes are a series of self-quenching counter tubes designed to cover the general field of beta, gamma, X-ray, and cosmic ray measurements. In some cases they have been tailored to meet the needs of laboratory reliability and accuracy and in others they are adapted to the more rugged requirements of portable operations.

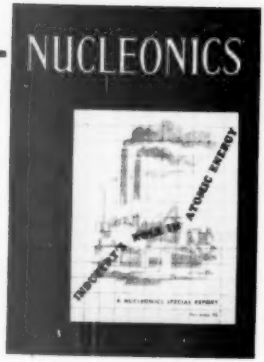
The types 1B85, 1B106, 1B124, and 1B125 are counter tubes for the field measurement of beta, gamma, and cosmic radiation.

The types 1B86, 1B87, 1B88 are gamma counter miniature and sub-miniature glass tubes for lead mounting on chassis boards or printed circuits.

COMPONENTS DIVISION

The Victoreen Instrument Co.

3800 PERKINS AVENUE · CLEVELAND 14, OHIO



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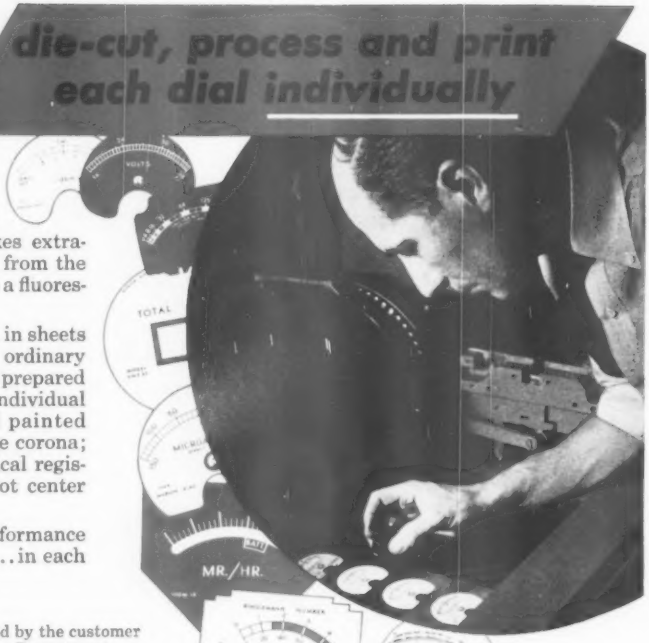
marion methods

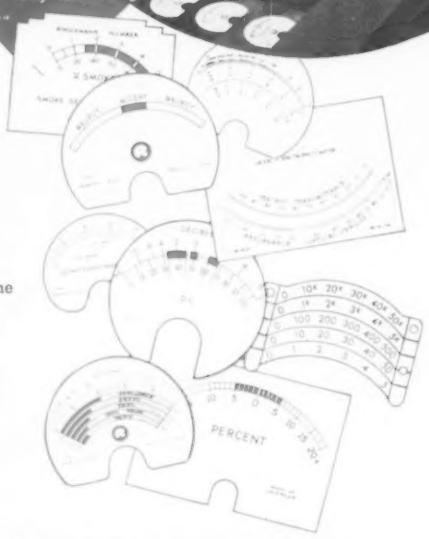
die-cut, process and print each dial individually



Because the accuracy of an indicating instrument is completely dependent upon the accuracy of its dial, Marion takes extraordinary care with each dial . . . from the simplest black and white type to a fluorescent type of seven colors.

Marion dials are never printed in sheets and then stamped out, as are ordinary dials. Each Marion dial is die-cut, prepared and printed *separately*. This individual handling guarantees finished painted edges, which reduces high voltage corona; it also assures accurate mechanical registration of the dial with the pivot center of the instrument.

Precision and dependable performance are built into every Marion dial . . . in each step of manufacture.



Preliminary Operations . . . Dial data furnished by the customer is carefully checked by Marion's Engineering Department. After Engineering OK, data and suggested layout are sent to the Art Department.

The dial scale is drawn 4 to 6 times "life size," then the drawing is photographed and reduced to the proper size.

Preparation of Plates . . . After photography, a positive print is made. Color separations are made by hand, and deep-etched zinc plates for offset lithography are produced. The offset process is used to assure sharp printing definition and good color.

Preparation of Dial Blank . . . Each metal dial blank is thoroughly rinsed and vapor de-greased. Then, three separate coats of special fume and age-proof eggshell-white lacquer are applied. This lacquering technique gives a surface that will not chip, flake, fade or discolor.

Registering . . . After careful inspection, dial blanks are securely mounted on the printing press. Each blank is individually adjusted, and the printing plate is positioned exactly. This step ensures perfect registration for multi-color printing.

Printing and Drying . . . Each dial is then printed separately. After special inks of each color are applied, dials are baked for 15 to 20 minutes to set the ink. This process eliminates smudging, and minimizes the amount of lint picked up during drying. Dials are thoroughly inspected again before they are mounted on Marion instruments.

Other Marion Methods. Marion's method of assuring the top accuracy and service of each dial by individual handling is only one of a number of methods which Marion is presenting in the hope that some of them will help you as they have helped us. We will be pleased to send more information if desired.

MARION ELECTRICAL INSTRUMENT CO., 431 CANAL ST., MANCHESTER, N. H.

marion meters

MANUFACTURERS OF MARION Ruggedized PANEL METERS

WITH VEECO TYPE R BELLOWS VALVES

High speed results from large stem lift and extremely short flow path through the valve.

The simple two-piece construction insures ease of installation and maintenance.

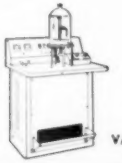
Type R valves are made from bar stock and guaranteed absolutely leak proof by test on the Veeco Leak Detector.

Sizes range from ⅛" up to 1½" for either solder or pipe connections, in brass construction; also available in 100% stainless steel, in certain sizes.

Hundreds of installations have proved these valves highly satisfactory for pump lines, manifolds, and all high vacuum applications.

Other types of Veeco Valves for manual, pneumatic or electrical operation are made in sizes up to 8 inches. Special valves built to specifications. Your inquiry invited.

WRITE FOR BULLETIN RV-6


VACUUM SYSTEMS

VALVES

LEAK DETECTORS

VACUUM-ELECTRONIC ENGINEERING CO.

756 THIRD AVENUE • BROOKLYN 32, N.Y.

PRECISION RECORDING OF RADIOACTIVITY

another

OHMART

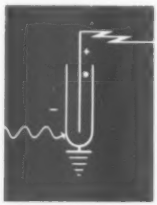
development in

NUCLEAR RADIATION MEASUREMENT

The unique Ohmart Cell now is available for use with a high-impedance current recorder. Utilization of the Ohmart Cell, which converts radio-active energy directly into electrical energy and thus requires *no high voltage power supply*, results in an installation of unparalleled simplicity of operation. The new Model RT Cell, designed for precision measurement of gamma radiation, may be used for continuous monitoring of ambient radiation such as is encountered in health physics work, or may be used to follow continuous processes where gamma ray activity is present. The Cell is built with a centrally located well, in which a sample may be placed, providing nearly 100 percent geometry. When connected to the recorder for sample measurement, a permanent record of production is made which not only shows the number of samples tested, but also records the amount of activity in each sample. The Cell may also be used with a number of standard indicating instruments similar to those used for pH measurement. When used with a recording or an indicating instrument, signal contacts may be included to sound high or low alarms, or pneumatically or electrically operated control mechanisms may be employed for the automatic control of processes.

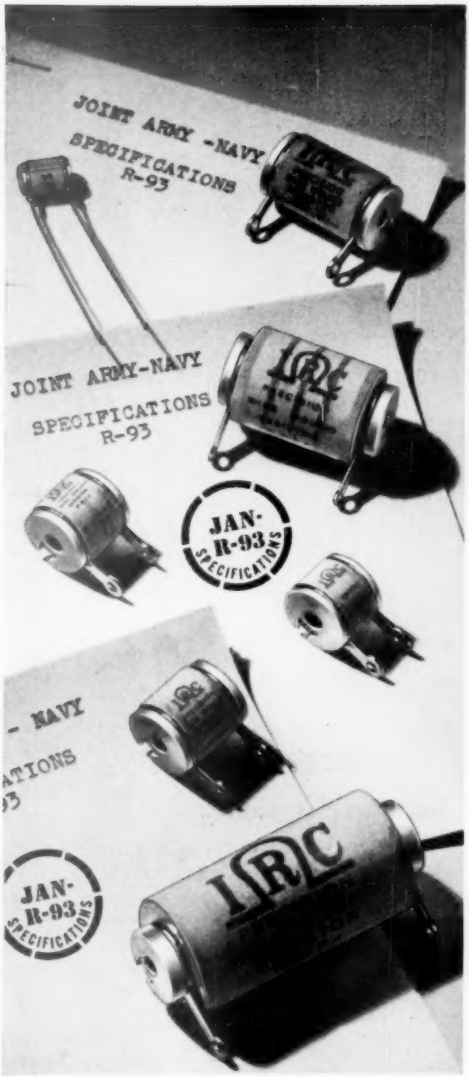
The sensitivity of the Ohmart Model RT Cell is such that, when calibrated for measuring samples placed in the well, one tenth full scale reading on the recorder is equal to five microcuries of radium. When calibrated for measuring ambient radiation, one tenth full scale reading is equivalent to two milliroentgen per hour. Accuracy of the Cell is not affected by changes in ambient temperature, barometric pressure, or relative humidity, and length of lead between Cell and instrument is not a critical value. Hence, Ohmart Model RT Cell installations may be used with complete confidence in virtually any location.

For detailed Information on recording or indicating installations, write The Ohmart Corp., 2345 Ferguson Road, Cincinnati 38, Ohio.



THE OHMART CORPORATION

2345 Ferguson Road, Cincinnati 38, Ohio.



UNBIASED TESTS PROVE THESE NEW PRECISION WIRE WOUNDS

MOST RELIABLE AND STABLE OF ALL!

This is no flight of fancy. Tested side-by-side with competing resistors, on the most modern testing equipment, IRC's new Type WW Precision Wire Wounds proved vastly superior in reliability and stability!

Actually, new Type WW's *far surpass JAN-R-93 characteristic B Specifications.* Severe cycling and 100-hour load tests resulted in virtually zero changes in resistance. Other stringent tests proved Type WW's high mechanical strength, freedom from shorting, resistance to high humidity.

	Original Resist.	1st Cycle % Chge	2nd Cycle % Chge	3rd Cycle % Chge	4th Cycle % Chge	Resist. at End of 100 hrs. load	Total % Chge	% Chge from Last Temp. Cycle to End of 100 hrs. load %	Resistance Chge at End of 100 Hrs. Load only % (no cycling)
1	100,010	+.04	+.04	+.05	+.05	100,050	+.04	−.01	100,040	−.02
2	100,000	+.03	+.04	+.03	+.05	100,060	+.06	+.01	100,000	0
3	100,000	+.01	+.02	+.02	+.05	100,000	0	+.05	100,050	−.02
4	100,000	+.02	0	+.02	+.02	100,000	0	−.02	100,040	−.01
5	100,010	+.03	+.04	+.04	+.05	100,000	0	−.05	100,030	−.03
6	100,000	0	+.03	+.04	+.04	100,100	+.1	+.06	99,980	0
7	100,000	+.04	+.05	+.04	+.04	100,070	+.07	+.03	100,000	0
8	100,000	+.03	+.05	+.05	+.05	100,050	+.05	0	100,000	0
9	100,000	+.04	+.03	+.05	+.04	100,010	+.01	−.03	100,050	0
10	100,000	+.02	+.02	+.02	+.04	100,010	+.01	−.03	100,000	0
11	100,000	0	+.01	+.01	+.03	100,000	0	−.03		

NEW WINDING FORMS hold more wire, giving higher resistance values. Non-hygroscopic ceramic assures high insulation qualities, high mechanical strength and low coefficient of thermal expansion.

NEW WINDING TECHNIQUE eliminates possibility of shorted turns or winding strains. All wire used in construction is given rigid insulation tests of special enamel coating, and special attention is given to insure transfer of wire to winding form without strain or break in insulation.

NEW TYPE INSULATION withstands humidity, assures long life. Winding is multiple vacuum impregnated with new IRC-developed compound which retains same consistency throughout entire range of temperatures to which resistors are exposed. Neither glassy hard nor tacky soft under any condition, this prevents wire strains, provides stability and freedom from noise.

NEW TERMINATIONS are rugged lug terminals for solder connection. These provide dependable and strain-free winding terminations. Only WW-10, because of small size, is provided with wire lead termination 2" long.

Send for full technical data on these new Precision Wire Wounds—and be sure to ask about our Industrial Service Plan. It enables your IRC Distributor to give you 'round-the-corner delivery of experimental or pilot-run quantities—right from local stocks.

Wherever the Circuit Says ~~~

Power Resistors • Voltmeter Multipliers
Insulated Composition Resistors
Low Wattage Wire Wounds
Controls • Voltage Dividers
Deposited Carbon Precisions
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IRC

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401 N. BROAD STREET, PHILADELPHIA 8, PA.
In Canada: International Resistance Co., Ltd., Toronto, Licensee.

A

INTERNATIONAL RESISTANCE COMPANY
419-A BROAD STREET, PHILADELPHIA 8, PA.

Please send me additional information on IRC Type WW Precision Wire Wound Resistors ( )—Name and address of local IRC Distributor ( ).

*Name*_____

*Title*_____

*Company*_____

*Address*_____

*City*_____ *State*_____

Simplicity is

NEW simplified
Recording Potentiometer
by WESTON

built to the same high standards of
accuracy . . . sensitivity . . . durability
as all instruments bearing this name.

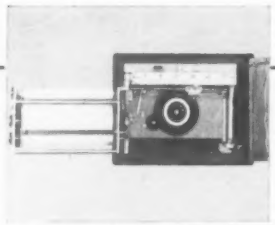


Chart frame swings out full 180° on straight pivots, chart remaining in time sequence. Charts easily installed in matter of seconds.

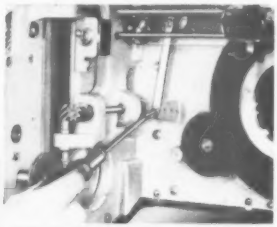
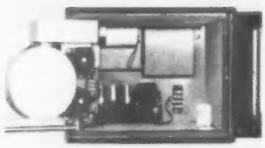


Chart speeds changed by simple screwdriver adjustment. Ranges quickly changed, too, by simply inserting correct range standard.



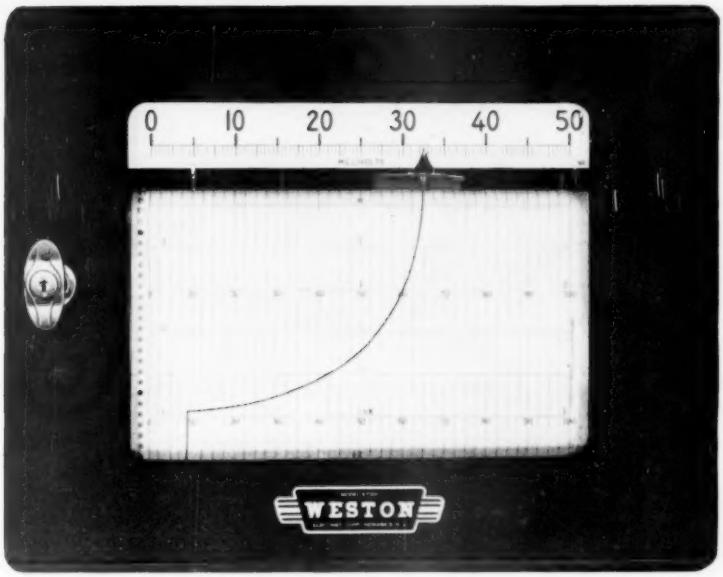
Note extreme simplicity both mechanical and electrical; as well as complete accessibility for quick maintenance and servicing.

WESTON TAG 9128

WESTON *Instruments*

INDICATE . . . RECORD . . . CONTROL

the keynote!



With this new high-speed Recording Potentiometer WESTON sets a new pattern for sound, simplified design . . . for simplicity and economy of maintenance . . . and for sustained high accuracy and sensitivity. With fewer components . . . with all assemblies greatly simplified and quickly interchangeable . . . with all adjustments including range changes made quickly on-the-line . . . with new compactness, ruggedness, and sustained high accuracy . . . this modern instrument will cut costs, and eliminate headaches wherever instrumentation is involved. You will want all the facts. Ask your local WESTON Representative, or write direct . . . WESTON Electrical Instrument Corporation, 617 Frelinghuysen Avenue, Newark 5, New Jersey . . . *manufacturers of Weston and Tag Instruments.*

Chart installation is Simpler — with new accessibility, and no loose parts to handle, chart can be installed in half the usual time. The chart drive has been simplified, made more positive, too.

Chart speed changes are Simpler — exclusive multi-speed chart drive permits instant selection of five different speeds with ordinary screwdriver. Speeds doubled or quadrupled by two simple gear changes.

Changing ranges is Simpler — you just insert correct range standard and tighten with screwdriver. Reference junction compensation changed in like manner. *No soldered connections used.* Universal slide wire needs no changing.

Pen and carriage are Simpler — pen quickly, easily filled without removal, or taking instrument out of service. Pen won't clog, never pumps or syphons-off, needs no priming after initial starting. One-piece pen carriage has oil-less bearings and is driven by woven stainless steel cable.

New Simplified ruggedness—all parts amply proportioned for strength and rigidity, to maintain mechanical alignment under tough usage.

All maintenance is Simpler — plug-in type amplifier, for example, removed in a jiffy. Liberal use of oil-less bearings reduces lubrication problems. No on-the-job soldering required.

NOW! Fill Your Needs

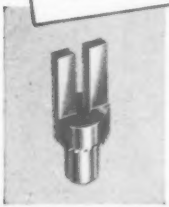
FOR ALL TYPES OF ELECTRIC AND ELECTRONIC COMPONENTS

custom or standard the guaranteed components

SILVER-PLATED BRASS TERMINAL LUGS

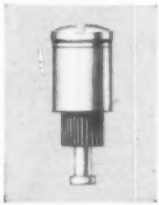
Short Lugs. For low "headroom" applications. Mounted heights from $\frac{3}{32}$". In shank lengths for 6 board thicknesses, starting with $\frac{1}{64}$".

Turret Lugs. With 2 soldering spaces for 2 or more connections. Sizes range from $\frac{1}{32}$" to ¼" terminal board thicknesses. Mounted heights from $\frac{3}{32}$".



Split Lugs. For potted units where later soldering is advisable. Also standard applications. Hole through shaft allows top or bottom wiring. Fit standard board thicknesses from $\frac{1}{64}$" through ¼". Mounted heights from $\frac{5}{32}$".

Double End Lugs. Provide terminal posts on both sides of board. Through connection for easy wiring. For board thicknesses from $\frac{1}{32}$" to $\frac{1}{16}$". Mounted heights from $\frac{3}{32}$".



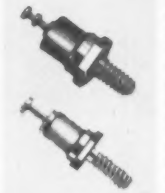
Combination Lug. Removable screw permits mounting components directly to screw end. Also provides removable link connections at screw end. 3 sizes, $\frac{5}{16}$", $\frac{11}{32}$", ⅜" diameter. Bright alloy plated for easy soldering.

HARDWARE

Handles in nickel-plated brass are available in 3 sizes ranging from $3\frac{5}{16}$" length to $6\frac{3}{4}$" length. Black alumilite aluminum handle available in $4\frac{3}{4}$" length. Ferrules available on brass and aluminum handles.

Other Hardware includes tube clamps, panel and thumb screws, combination screw and solder terminals, shaft locks, terminal board brackets, standoff mounts, etc.

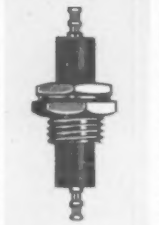
INSULATED TERMINALS



Phenolic. ¼" diameter, in rivet or screw stud type. Voltage breakdown from 4800 — 11,000 V at 60 cycles RMS.

Ceramic. Silicone impregnated. 5 lengths of dielectric. Voltage breakdown ratings up to 5800 V. Over-all heights range from ⅜", including lug. For high electrical stresses over a broad humidity range. Cadmium plated studs. Brass terminals plated for soldering.

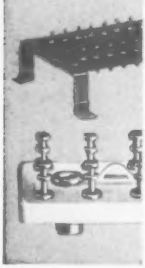
INSULATED FEED THROUGHS



Phenolic. Approved XXX material. Brass bushings, nickel plated. Brass through-terminals, silver plated for easy soldering. Rugged, withstand shock and vibration. Two sizes: for ¼" and ⅜" mounting holes.

Ceramic. Silicone impregnated. Threaded for ¼" hole mounting. O.A. length ⅞". Voltage breakdown 4800 RMS at 60 cycles.

TERMINAL BOARDS



Phenolic. Available in various widths and terminal arrangements from ½" wide to 3" wide. Thicknesses: $\frac{3}{32}$", ⅛", $\frac{5}{16}$". All boards in 5 sections scribed for easy separation. Special boards made to your specifications.

Ceramic. Silicone impregnated. Type X1986 with 8 lugs staked in two rows. Standoffs riveted and soldered to ground strap for good grounding at R.F. frequencies. 1¼" long, ⅞" wide. All metal parts plated. O.A. mounted height: $\frac{33}{64}$".

SLUG TUNED COILS

Phenolic. 3 sizes: $\frac{27}{32}$", 1⅛", and 2" high. 5 standard windings — also special windings or as high-quality phenolic coil forms.

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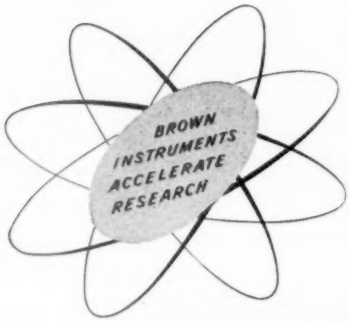

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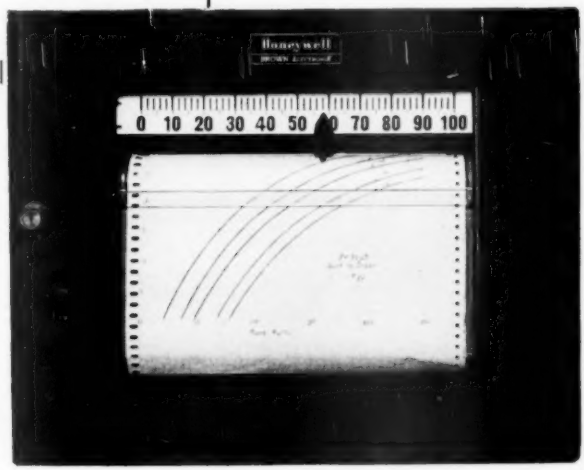

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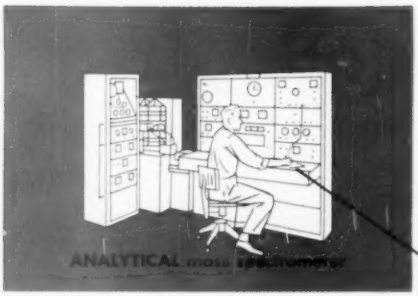

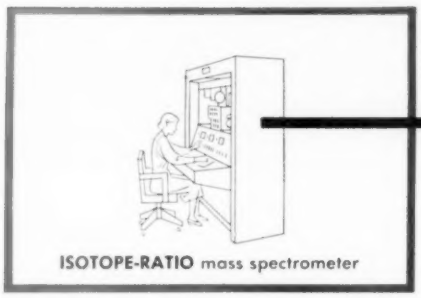

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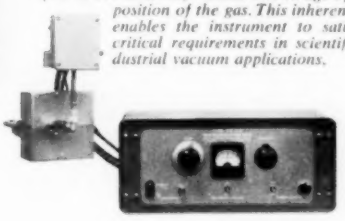

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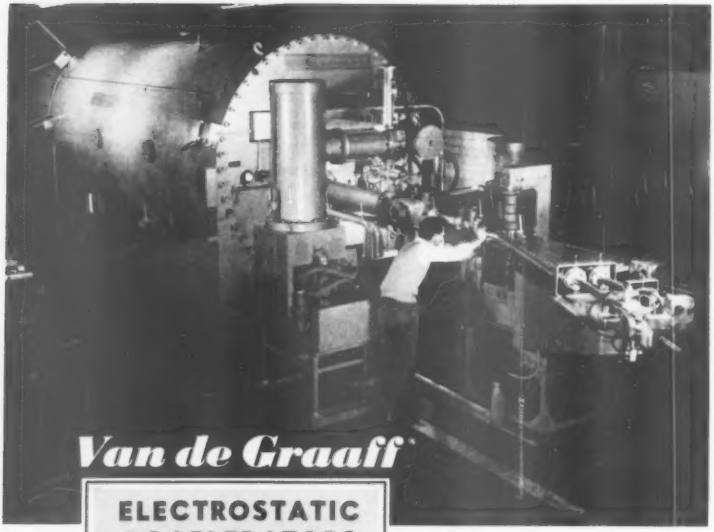

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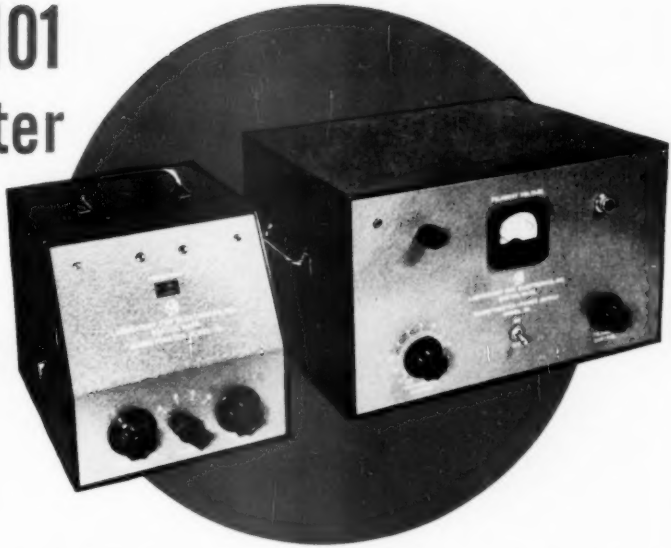

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Modulation Sweep Width Range
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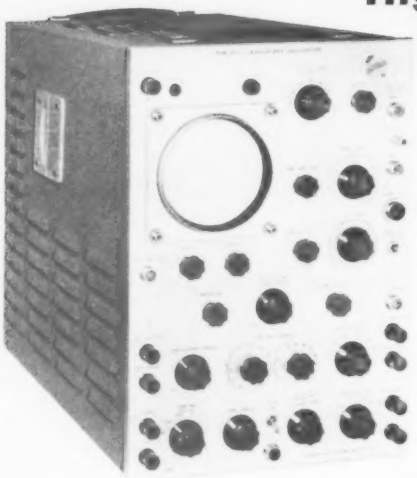

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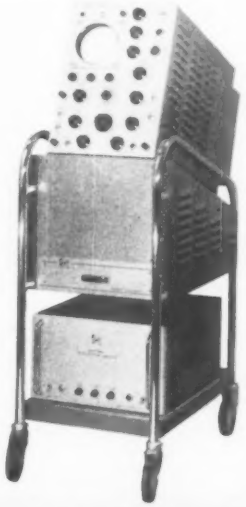

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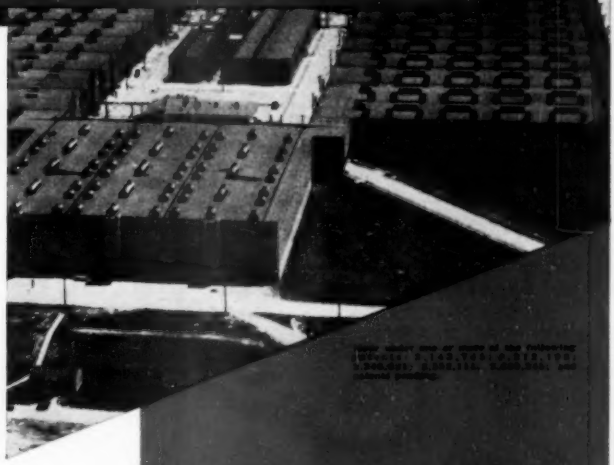

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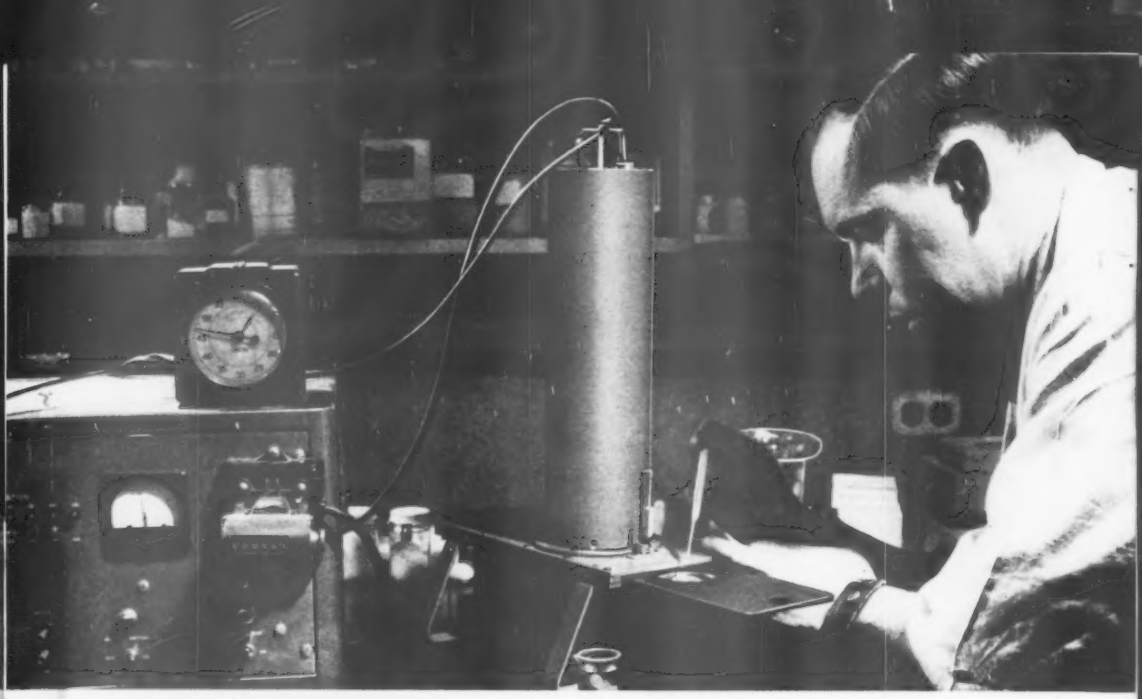

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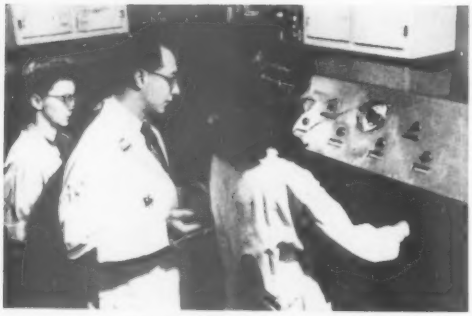

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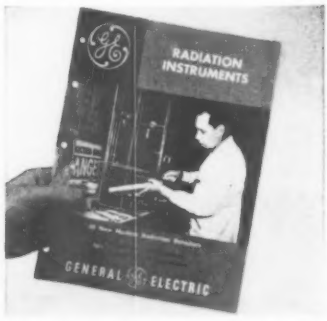


Write for new 8-page catalog of General Electric radiation detection instruments.

NUCLEONICS

JUNE, 1952

Industry's Role in Atomic Energy

The 16-page report which starts on p. 93 of this issue shows the very dramatic growth of the Government's atomic energy program. Although nearly $7-billion have already been spent over a period of ten years, it looks as if $5-billion more will be spent in the next few years.

There is no comparable growth pattern for any other industry in this country's history. In just one category alone—equipment and supplies—expenditures by the Atomic Energy Commission have been distributed through 41 different industries. Thousands of companies have been involved; some sought out this business, others had it come to them.

With the planned expansion of the program, the past growth is going to be multiplied many times. Capital investment will be increased by upwards of several hundred per cent.

However, despite this fabulous growth, we now stand on the threshold of an even more significant event—the entrance of industry into the atomic energy field for industry's own sake. For the past year, four industrial teams have been studying the economic feasibility of building power-producing nuclear reactors. It has just been announced that one of these teams—Dow Chemical Company and Detroit Edison—is going to spend $250,000 of its own money on the design of a reactor. It is also expected that the other three groups will invest additional money of their own in a continuation of their studies.

Thus, for the first time since the first successful controlled chain reaction ten years ago, we are going to have a full-fledged direct attack on industrial nuclear power. With this will come a concentrated study of a whole new range of problems. Although much of AEC's experience on reactors will be of use to these pioneering companies, this experience has come principally in connection with plutonium-producing reactors rather than with those that would produce significant amounts of power.

The original intent of the study teams was to design dual-purpose reactors—for the production of plutonium with power as a byproduct. It was felt that, since nuclear power would not be immediately competitive with conventional power, sale of plutonium back to the Government would be necessary to pay for part of the capital investment. However, there is no assurance that the plutonium market would last as long as would be needed for amortization purposes.

At least one of the teams plans to steer clear of this problem. It has set as its immediate goal the design of a *single-purpose* nuclear power plant which will produce power at competitive prices. To do this, this team will take an approach not yet used in AEC's reactor program. It appears that this may include the design of a homogeneous power breeder. Another possibility is that thorium and uranium-233—long-neglected in AEC activities—will come in for serious consideration.

Because of the unique problems faced in any approach along these lines, we estimate it may be upwards of ten years before such a plant could be put into operation.

However, there will be a shorter time scale for the groups planning to design and build *dual-purpose* plants. Although the reactors they design will be different from any yet built, these teams will depend heavily on available information. Their method will be to use an engineering approach and build a reactor quickly—a five-year target date is quite feasible. Once a power-producing unit is in operation, they can then gain experience for building single-purpose reactors.

With these four study teams actively at work, and with a number of new ones expected to get started shortly (NU, May '52, p. 72), we are truly approaching the time when peacetime applications will be significant. A new breed of technologist is coming to grips with a new class of problems. —*J.D.L.*

Locating Buried Radioactive Sources

How to design an efficient search procedure is described. Examples show that choosing the right source-to-detector elevation can, in certain cases, reduce search time and effort by as much as a third

By RICHARD I. CONDIT and J. D. GRAVES
Broadview Research and Development Burlingame, California

FINDING radioactive materials buried at shallow depths below the surface of the earth is a problem common to such tasks as exploring for uranium ores, recovering radioactive tracers, and evaluating possible subsurface contamination. Viewed as a problem in the location of buried treasure, the solution lies in evolving the optimum search procedure.

Optimum search procedure is that method of scanning any area, within which the treasure is equally likely to be, in such a manner as to locate it in the shortest possible time.

Scanning is generally done by a systematic search along some system of coplanar grid lines parallel to the surface of the area under examination. In terms of radioactive source strength, likely burial depth, and detector sensitivity, it means spacing these grid lines with the maximum possible separation consistent with the positive detection of the given source anywhere within the grid lines.

To specify this maximum or optimum grid-line separation, we need to know source strength, burial depth, and detector sensitivity. However, one generalization is possible. Whatever the grid-line separation, the search should be conducted at *the elevation* where the radiation intensity is the maximum.

Thus we need the answer to the following question: At a given surface distance away from a buried radioactive source, at what elevation is the radiation intensity highest?

Method of Analysis

For insight into the answer to this question, we have examined the simple situation of a point source of cobalt-60 buried beneath a plane surface, as shown in Fig. 1. For this case, the radiation intensity I at the point in question is given by the expression

$$I = \left(\frac{K}{R^2}\right)(e^{-\mu r}) \qquad (1)$$

The denominator of the first term

takes care of the fall-off in intensity with the inverse square ($1/R^2$) of the separation of source and detector, while the numerator (K) provides for the source strength and the proper units. The second term takes account of the absorption of radiation in the earth (absorption coefficient μ and penetration distance r).

Compared to these terms, the absorption of radiation in the atmosphere is negligible and, therefore, has been neglected.

Introducing the necessary variables of X = distance away, Y = elevation, and L = depth of burial, it is seen that

$$R^2 = X^2 + (Y + L)^2$$

and

$$r = L\frac{R - r}{Y}$$

A simple relation for r follows if we restrict our conditions to $R \gg r$. Then r can be neglected in the numerator and

$$r = L\frac{R}{Y}$$

Moreover, $R \gg r$ implies $Y \gg L$, so the expression for R^2 can be approximated with sufficient accuracy as

$$R^2 = X^2 + Y^2.$$

Therefore,

$$r = L\frac{\sqrt{X^2 + Y^2}}{Y}$$

Rewriting the expression for the radiation intensity in terms of these more useful variables, gives

$$I = \frac{K}{X^2 + Y^2} e^{-\mu L\frac{\sqrt{X^2+Y^2}}{Y}} \qquad (2)$$

limited in its validity to $R \gg r$ which means $Y \gg L$.

This expression has been evaluated for a buried point source of Co^{60} with a strength of one curie. The values for the absorption coefficient were derived from Hirschfelder *et al.** as

$$\mu = 0.03 \text{ for } 0 < r < 10 \text{ cm}$$
$$\mu = 0.04 \text{ for } 10 < r < 50 \text{ cm}$$
$$\mu = 0.05 \text{ for } 50 < r$$

Care has been taken to restrict the range of our variables to $Y \gg L$; that is, the elevation where the radiation intensity is evaluated is always much greater than the depth of burial. This condition is actually no restriction, since the elevations of interest (including the optimum elevation) are always large with respect to the burial depth.

*J. O. Hirschfelder, J. L. Magee, M. H. Hull, *Phys. Rev.* **73**, 852 (1948)

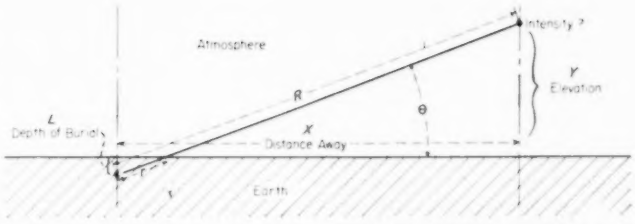


FIG. 1. Diagram of buried radioactive source showing point where intensity is to be detected. Detector-source separation is *R*. Radiation penetration of the earth is *r*

Intensity Determinations

The radiation intensity (in roentgens per hour per curie of Co^{60}) as a function of elevation and surface distance away is given for two different depths (15 cm and 30 cm) in Fig. 2.

If attention is given to the solid lines representing the 15-cm burial, it can be seen that with the detector at the fixed height of 100 cm, as one moves out and away from the source, the radiation intensity falls off slowly at first, and then very rapidly. At the next higher elevation—500 cm—the initial intensity, while lower, remains near its initial value out to a greater distance away before it falls off rapidly.

In fact, the curve for 500 cm crosses the falling curve for 100 cm, and at distances beyond this intersection the intensity at 500 cm elevation is everywhere greater than that at 100 cm elevation. The intensity at each of the higher elevations behaves in a similar way.

As an example of the use of these intensity curves, consider the problem of locating a 10-mc Co^{60} source buried 15 cm deep with a detector having a sensitivity of 0.01 mr/hr. This source strength of 10^{-2} c and detector sensitivity of 10^{-5} r/hr determine the minimum intensity where detection is possible as 10^{-3} r/hr/c of Co^{60}. A horizontal dashed line marks this point on the intensity axis of Fig. 2. The intersections of this line with the curves for various elevations give the horizontal distances at which detection under the conditions named would just be possible.

From this, it is seen that the detector carried 100 cm high could detect the source out to a distance of about 600

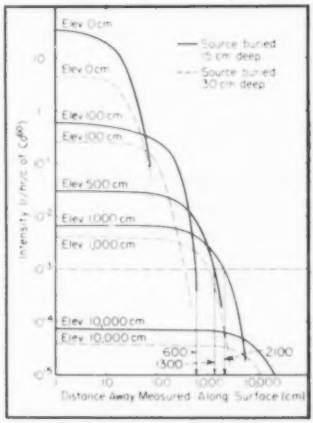


FIG. 2. Radiation intensity as a function of elevation and surface distance away for two burial depths (based on Eq. 2). (Intensity at surface is included for comparison based on a different equation.)

cm. Carried 500 cm high, however, it would be able to detect out to 1,300 cm. And, better still, if carried 1,000 cm high, it would detect the radiations from the buried source clear out to 2,100 cm.

Thus the first significant feature of this study is revealed. The ultimate distance away at which a buried radioactive source can be detected is determined in large measure by the height of the detector above the surface during the search procedure.

Using the same example, a search with the detector 100 cm above the earth should be conducted along grid lines spaced 2×600 cm = 1,200 cm apart; with the detector 500 cm high, a spacing of 2,600 cm would suffice; while 1,000 cm up, one could get along with a grid spacing of 4,200 cm. In other words, by merely changing the

elevation of search from 100 cm to 1,000 cm, one can explore the same region with the same effectiveness with less than one third the time and effort. Thus the elevation where search for buried radioactive materials is to be carried out deserves real attention.

Any detection under the conditions mentioned that is attempted at still higher elevations, say, 10,000 cm, would *never* be successful. Then the detector is too high and the level of intensity required for detection is everywhere greater than the intensity existing at that elevation.

If curves for all possible elevations in Fig. 2 were to be filled in, an envelope to the right-hand side of this family of curves would be developed. This envelope would give, for any distance away, the best elevation for search.

Optimum Search Conditions

The left-hand graph of Fig. 3 shows the optimum elevation for any distance away for two burial depths (15 cm and 30 cm). Looking for the same features shown by Fig. 2 in our previous example (optimum elevation 1,000 cm occurring at a horizontal distance of about 2,100 cm), it can be seen from the solid line in Fig. 3 that at about 2,100 cm away the optimum elevation is about 1,000 cm. Thus the two figures check.

The dotted curve for 30 cm burial shows that the optimum elevation 100 cm away is 100 cm up; at 1,000 cm away, about 1,000 cm up; at 10,000 cm, 10,000 cm up; etc. In other words, an apparent relation exists between optimum elevation and distance away which is solely dependent on depth of burial. This suggests that other analytic descriptions may be more appropriate than those we have used to define the optimum search conditions. Accordingly, we shall examine these relations closer.

For a given distance away, the optimum elevation for search can be determined by finding the elevation where the expression for the radiation intensity has a maximum value.

To do this, we take Eq. 2, keep X, L, and K constant, find the derivative dI/dY, and set it equal to zero. Thus

$$\mu L X^2 \sqrt{X^2 + Y^{*2}} - 2Y^{*3} = 0 \quad (3)$$

where Y^* represents the optimum Y.

The solution of this equation is facilitated by a change in variables. For this purpose, search angle θ, a new variable, is introduced. It is the angle between the detector-source line and the ground surface. See Fig. 1.

Tan $\theta = Y/X$, or tan $\theta^* = Y^*/X$. Rewriting Eq. 3 in terms of the optimum angle of search θ^* gives

$$\sin^3 \theta^* + \frac{\mu L}{2} \sin^2 \theta^* - \frac{\mu L}{2} = 0 \quad (4)$$

Thus θ^* is a function of L (and μ) only and the solution of this equation is

$$L = \frac{2 \tan^2 \theta^* \sin \theta^*}{\mu} \quad (5)$$

This expression gives for any burial depth L the optimum angle of search θ^*. The result is plotted as the graph on the right-hand side of Fig. 3.

This graph shows that a given depth of burial determines a single-valued optimum relation between distance away and elevation in terms of

$$\theta^* = \tan^{-1} \frac{\text{opt. elev.}}{\text{dist. away}}$$

The angle θ^* and the ratio of optimum elevation to distance away are independent of the source strength and the detector sensitivity.

Any actual situation involving a given source strength and detector sensitivity will tell how far out along the optimum search vector detection should be attempted. From this determination, grid-line spacings and elevations of search would follow.

By checking the two graphs in Fig. 3 against each other, one can see from the right-hand curve that a burial depth of 30 cm specifies an optimum angle of search of 45 degrees. This was the implied angle in our previous example from the left-hand curve where the 30-cm-deep dotted line correlated 100 cm away with 100 cm high, 1,000 cm out with 1,000 cm up, etc.; here $\theta^* = \tan^{-1} 1 = 45$ degrees.

The more important graph in Fig. 3 is the right-hand one. It shows the optimum search angle as a function of the depth of burial. This optimum angle is 0 degrees for sources on the surface, 30 degrees for sources at a depth of about 8 cm, 60 degrees for sources at about 100 cm, and approaches 90 degrees for sources at very great depths. In any practical situation where the depth of burial has a known or probable value, Fig. 3 gives the corresponding optimum angle.

Along the direction of the search angle above the surface, the radiation intensity falls off as the simple inverse square. The source strength and the detector sensitivity will determine how far out along the optimum-search-angle vector the search should be conducted. In this manner the maximum distance away (or grid spacing) and the optimum elevation for detection are specified.

How Critical Is Optimum Value?

It has been shown that the maximum radiation intensity at any given large distance parallel to the surface from a source buried a finite depth occurs above the surface, and that the search for buried radioactive materials is best attempted with detectors at elevated positions.

It is also important to determine just how critical the optimum value of the elevation may be. Accordingly, information is required about the values of the radiation intensity at a fixed surface distance away as a function of the elevation (and in the vicinity of the optimum elevation). This can be obtained for any given case by plotting intensity values from Eq. 2.

As an example, Fig. 4 is a typical result. It shows the variation in the relative radiation intensity with elevation at a horizontal distance of 1,000 cm from a source buried 30 cm deep. Near the elevation of maximum intensity, the intensity decreases more rapidly with decreasing elevation than with increasing elevation. The actual maximum is not especially critical as to elevation.

The important thing is to get up away from the surface and to operate in the general vicinity of the optimum elevation. Operating higher than the optimum elevation will reduce the signal strength somewhat but not anything like the reduction that accompanies operations at lower elevations. (The intensity at the surface is far to the left on this curve, many orders of magnitude lower than anything shown.)

An appreciation of the physical features involved in determining these relations for buried sources may be valuable. Because of the geometry of our search procedure, we find, at a given surface distance away, a radiation intensity which varies with elevation as a result of the competition between total inverse square diminution and exponential absorption in the

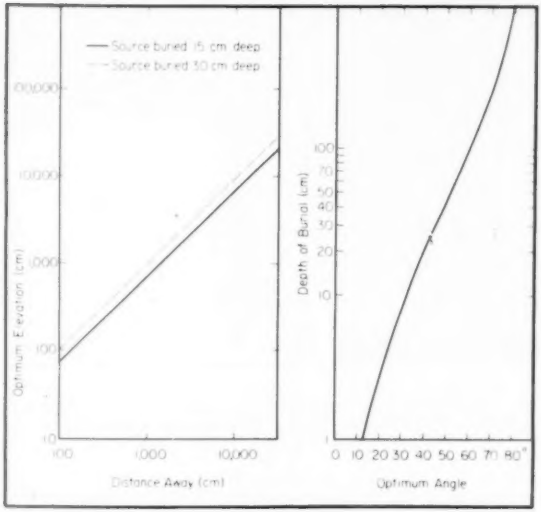


FIG. 3. Optimum values of search parameters. Left graph shows optimum elevation as function of distance away for two burial depths. Right graph shows optimum angle of search as function of burial depth

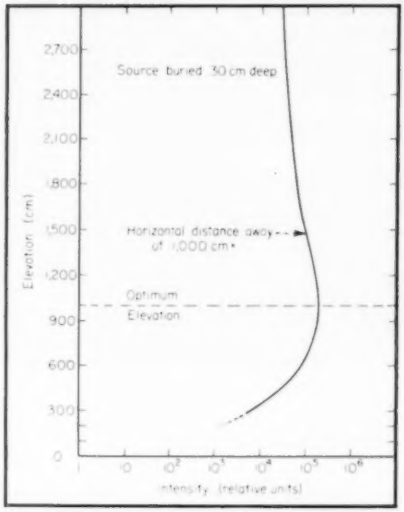


FIG. 4. Relative radiation intensity as function of elevation for fixed horizontal distance away of 1,000 cm and fixed burial depth of 30 cm

earth. At this fixed surface distance away, the higher the elevation, the greater is the inverse square loss in intensity due to the greater source-detector separation. At the same time, however, the higher the elevation, the less earth is penetrated and the less is the loss in intensity due to absorption in the earth. These two opposing processes actually yield a maximum in the radiation intensity at some elevation above the surface—the optimum elevation.

At lower levels, the increased earth absorption exceeds the decreased inverse square loss. At higher levels, the intensity also falls, but this time because the increased inverse square loss exceeds the reduction in the earth absorption.

Adaptability of Design

To extend to actual field conditions the foregoing information which is based on a simple *point* source of radioactivity buried below a *plane* surface, we can briefly note the following for cases where:

The topography is nonplanar. The advantages of elevated detection are likely to be as much or even more than those derived here for the plane surface. The optimum elevation is determined by the minimum product of inverse square attenuation and ground absorption. Uneven surfaces will generally be expected to contribute more absorption at the elevations about the optimum value than plane surfaces. Therefore, if the optimum elevation for a given nonplanar topography is different from that for a plane, it is likely to be higher.

The buried source is not a point and has extended dimensions parallel to the surface. The advantages of elevated detection will be even more than those derived here for the point source. With extended sources, the decrease in intensity with distance is less than the inverse square of the source-detector separation, which is characteristic of point sources. Therefore, the fall-off in intensity about the optimum elevation will be diminished and the optimum for extended sources will be expected at greater elevations.

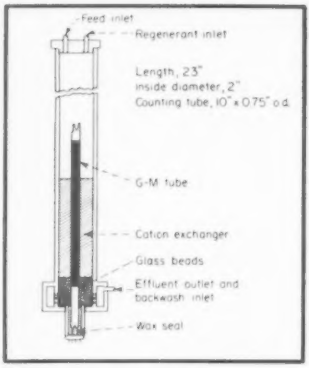
The source is at an unknown depth or is distributed over a considerable range of depths. The procedure for location will still follow the general pattern outlined for the point-source situation. The radiation from sizeable sources of moderate strength which are entirely buried at very great depths will be so highly absorbed by the earth in traveling up to the surface that it will be undetectable. Such materials can never be located from above the surface and may be dismissed from further consideration. Radioactive materials at all other depths between the surface and this ultimate depth will be more readily located from elevated positions of detection than from the surface. Material buried only 1 cm deep has an optimum angle of search of over 10 degrees. Since the intensity along the 10-degree search vector falls off much faster coming down toward the surface than it does in going up to higher elevations (elevations which will be optimum for source materials deeper than 1 cm), it proves desirable to search at elevated positions in all cases.

Conclusions

The design of the optimum search procedure for any practical field problem can be determined only from a detailed consideration of the actual features of that problem. The appropriate design principles, as introduced here, exist. Their implementation is important, for the advantages to be gained by using a properly designed system of exploration are bound to be considerable in terms of both manpower saved and material located.

Experience in the field in locating buried radioactive sources according to these principles, while not extensive, is sufficient to indicate experimental verification of the results of this study.

1 COMPLETE ASSEMBLY. Special G-M tube, surrounded by ion-exchange resin bed, is connected to counting-rate meter that feeds to recorder. Recorder plots build-up of activity on resin bed as a function of time or, at constant flow, as a function of the volume through the bed



2 DETECTOR UNIT. G-M tube used has 10-inch glass wall (30 mg/cm²), is centered in 200 cm³ ion-exchange resin bed (Dowex 50) that serves as concentrator

A METHOD FOR ESTIMATING

Low Levels of Radioactive Contaminants in Water

New column-type water monitor combines advantages of measuring low concentrations of activity with adaptability for continuous operation

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THERE ARE two general methods of evaluating the quantity of radioactive contaminants in water. One method consists of immersing a Geiger-Müller tube directly into the water stream. A second method of evaluating the activity level of a water supply consists of evaporating a large volume composite sample to dryness and counting the residue with an end-window type counter.

With the first method, the sensitivity for high-energy beta emitters is about 10^{-6} $\mu c/cm^3$, or ten times higher than the suggested maximum permissible concentration acceptable for long-term ingestion. There is a tendency for immersion-type monitors to become contaminated with inert materials and small amounts of active emitters. This type of monitor is satisfactory if it is necessary only to observe the approach to a dangerous concentration necessitating a restriction on water use.

The sensitivity of the second method is dependent upon sample volume, quantitative transfer of the residue, and judicious evaluation of the self-absorption correction necessitated by the inert solids. The evaporation method is neither continuous nor rapid, but lends itself readily to available instrumentation and presents no problem of contamination build-up on equipment components.

From these considerations, it became apparent that a need existed for a water monitor that would be capable of both measurement of low concentrations of activity and continuous operation. The illustrations on these pages show an apparatus adaptable to this purpose, which was developed at Oak Ridge National Laboratory.

The components of this monitor and its G-M tube are described in illustrations 1 and 2, with a notation on tube sensitivity in illustration 3.

The complete unit was calibrated by adding aliquots of a six-month-old

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mixed-fission-product solution to 20-gallon volumes of tap water. The results of the calibration are plotted in illustration 4. As expected, a straight-line function was found that can be represented by an equation of the type

$$\text{dpm/ml} = \frac{1}{k} \times (\text{recorded cpm/liter})$$

where k is essentially the counting efficiency with the necessary conversion factors. The slope can be determined in counts per minute per either liter or gallon. A recording from a typical run is reproduced in illustration 5.

Regeneration

A high-capacity, strong-acid-type resin in the hydrogen form was used because it was found to be an efficient exchanger for better than 90% of the fission products. If quantitative removal of the active isotopes were desired, it would be possible to use a mixed-bed exchanger. Using the cation exchanger makes it possible to put through a large volume of water before the resin becomes saturated with inert salts.

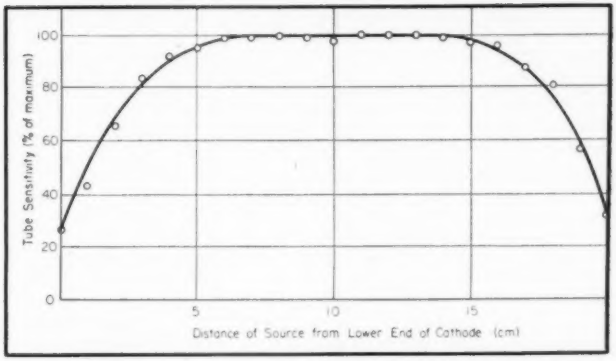
The maximum volume that can be monitored before the unit must be regenerated is a function of the total dissolved solids, the bed volume, and the resin capacity. With the unit described, having a 200-cm³ resin bed, it is possible to monitor 80 gallons of water containing about 120 ppm dissolved solids.

The use of the cation resin is advantageous also in that it simplifies regeneration of the resin bed. The unit described was regenerated by passing three liters of six molar hydrochloric acid through the bed at a flow rate of approximately 20 cm³/min. The hydrochloric acid converts the resin to the hydrogen form by replacing the calcium, magnesium, iron and active contaminant cations with hydrogen ions. When the resin is regenerated, the recorder activity level returns to background and the unit is ready for further use.

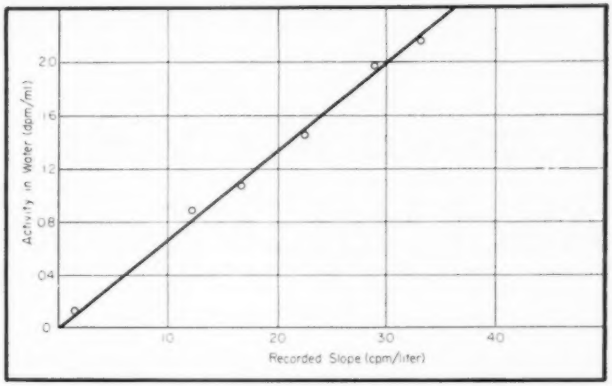
Adaptability

For use as a continuous monitor, the unit could consist of two columns; when one is operating as a beta-gamma monitor, the other is being regenerated.

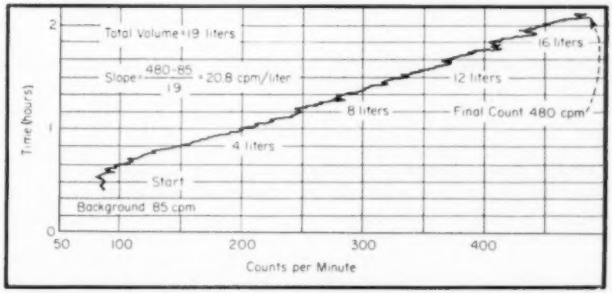
The unit is now being used to measure activity in the natural ground and surface waters in the Oak Ridge area.



3 **TUBE SENSITIVITY.** 10-inch glass G-M tube has internally silvered cathode length of 19 cm. For a divergent beam of radiation placed close to tube wall, tube sensitivity varies as function of source placement with respect to cathode length as seen in this graph. To obtain maximum counting yield, top of resin bed is maintained at a level about 5 cm below upper end of cathode



4 **CALIBRATION.** Monitor was calibrated by adding mixed-fission-product solution to tap water. Recording of build-up of activity was analyzed graphically by subtracting background value from total count and determining slope. Slope is directly proportional to activity level of feed solution. Calibration plot above shows known disintegration rate per milliliter of feed solution as function of counts per minute per liter obtained from recorder chart



5 **TYPICAL RECORDING.** In this copy of chart from typical calibration run, slope of line is 20.8 cpm/1. From graph in 4 above, slope can be seen to correspond to 1.35 dpm/ml

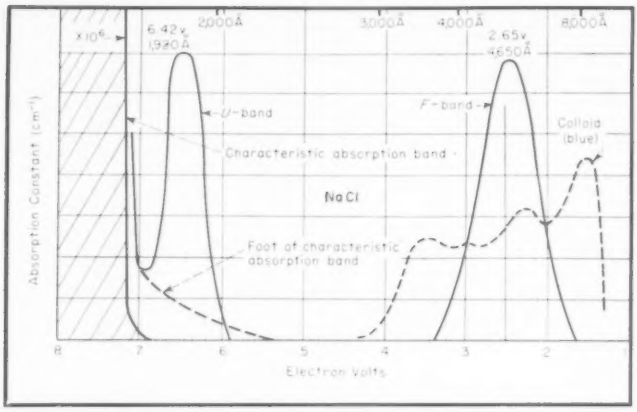


FIG. 1. Optical absorption bands in NaCl. A pure crystal is transparent throughout the visible spectrum. The fundamental lattice absorption sets in below 2,000 A, and the absorption constant rises to values of the order of 10^6. The *F*-band appears upon irradiation with gamma or X-rays. Introduction of alkali hydride produces the *U*-band. Colloidal agglomerations of alkali metal absorb red light, giving crystal a bluish color

Radiosensitivity of Alkali-Halide Crystals

"Dog-tag" dosimeters incorporating alkali halides are being considered for defense use. Dosage is measured by the color change that takes place in the crystal. To prevent fading and to enhance the visible color, the crystal must first be sensitized

By H. FRIEDMAN and C. P. GLOVER,* *U. S. Naval Research Laboratory, Washington, D. C.*

IF A DEVICE is to be worn by military personnel and civilians who may be exposed to A-bomb radiations, it must necessarily be small, simple, and inexpensive. It should be easily readable, remain permanently sensitized, and retain the indication of dose for at least several days with negligible loss.

Interest in dosimetry has focused attention on every property of materials that indicates sensitivity to accumulation of energy from roentgen radiation. These properties include the production of characteristic coloration, storage of photoconductivity and luminescence, alteration of piezoelectric constants, and change in chemical reactivity. Of all the radiosensitive changes, direct coloration is most attractive from the standpoint of developing a "dog-tag" dosimeter.

The most suitable materials for colorimetric dosimeters discovered thus

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far are crystals of the alkali halides. When properly sensitized, they meet most of the practical requirements and develop sufficient color to distinguish dosage in steps of approximately 50 r.

The literature of the past 50 years on the effects of radiation on materials (*1*) contains many descriptions of color changes suited to dose indication.

It was observed, for instance, that glasses used in the envelopes of X-ray tubes turned violet or brown. Some crystalline materials, such as the alkali halides, were discolored by X-ray or radium gamma-ray exposure in the same manner as when bombarded by cathode rays.

Coloration in many mineral crystals was associated with radioactive contaminations in the same areas. For example, smoky quartz could be duplicated by irradiation of clear quartz with X or gamma rays, and amethyst that had been bleached by baking recovered its original color when irradiated. The coloring of minerals by irradiation was found to be intimately associated with thermoluminescence. Heating the crystals discharged the luminescence and the color simultaneously, and subsequent exposure to X-rays restored both the color and ability to luminesce.

Properties of the Crystals

Recent surveys of the coloration of materials by X-rays indicated again that the alkali halides exhibit such coloration to an unusual degree. A characteristic color is produced in each alkali halide by any ionizing radiation whether it be far ultraviolet light, cathode rays, X-rays, or nuclear rays.

In spite of their sensitivity, the pure alkali halides are unsuited to practical dosimetry because the color induced by radiation fades relatively quickly. A solution to this difficulty was found in the use of crystals containing alkali hydride in solid solution. The various absorption processes involved in the coloration of pure alkali halides, crystals with excess metal, and crystals containing alkali hydride in solid solution are described briefly in what follows. The latter type of crystal develops stable visible color and meets many of the requirements of a personnel dosimeter.

F-Centers

Pure alkali-halide crystals are completely transparent in the near ultraviolet, throughout the visible spectrum, and into the near infrared. Only in the extreme ultraviolet is any absorption observed, and it takes the form of relatively sharp and very strong bands. In general, the lower molecular weight crystals are transparent farther into the ultraviolet region. The foot of the fundamental lattice absorption band occurs at about 2,200 Å in NaI, 1,900 Å in NaBr, 1,600 Å in NaCl, and 1,300 Å in NaF.

Visible coloration can be induced in the alkali halides by exposure to X-rays or gamma rays. Electrons ejected from negative halide ions, as a result of such irradiation, travel through the crystal until captured at vacant anion positions. These trapped electrons, or *F*-centers, are capable of absorbing visible light in a bell-shaped absorption band whose peak wavelength is characteristic of the particular type of crystal. Viewed in transmitted light, rock salt appears yellow, potassium chloride violet, and potassium bromide blue.

Every crystal contains a relatively large number of lattice defects capable of trapping electrons. Synthetic alkali halides generally possess somewhat more than natural crystals, and in specimens that have been strained or deformed the number of frozen-in holes is increased and the X-ray coloration correspondingly enhanced.

The density N of *F*-centers may be computed from the optical absorption coefficient K_{max} at the wavelength of the maximum of the absorption band, according to a simple relationship described by Hilsch and Pohl (*2*),

$$N = CK_{max} \qquad (1)$$

where C is a constant with a value of 4.45×10^{15} for KBr, 3.6×10^{15} for NaCl, and 2.6×10^{15} for KCl.

At low levels of irradiation, the density of *F*-centers increases almost linearly with dosage. At higher levels, the rate of production of *F*-centers falls off and the intensity of color approaches a saturation value. The saturation density is of the order of 10^{-2} *F*-centers per molecule, or about 10^{19} *F*-centers per cm³, in KBr. The rate of irradiation has no detectable effect on the number of *F*-centers produced by a given dose.

The ability of the eye to detect the presence of *F*-centers involves both the color and brightness of the transmitted light and the technique of viewing. Approximately 10^{14} to 10^{15} *F*-centers per cm³ of KCl, KBr, or NaCl represents the lower limit of detection with the unaided eye.

To interpret this concentration in terms of dosage, use may be made of a relationship observed by Alger (*3*) between N, the *F*-center concentration, and R, the roentgen dose,

$$N = aR^m \qquad (2)$$

where m has a constant value of 0.73 and a is 1×10^{12} for KBr, and 1.2×10^{13} for NaCl. Crystals of lower molecular weight develop more *F*-centers per roentgen, and a visibility threshold of 10^{14} to 10^{15} *F*-centers per cm³ corresponds to roughly 10 r to 100 r, depending on the type of crystal.

F-Center Formation

F-centers may be produced by processes other than those involving nuclear radiations; yet in each case the optical absorption bands are almost identical. Their location depends only on the closest spacing d between ions in the crystal according to the formula

$$\nu_{max} d^2 = 0.5 \text{ cm}^2/\text{sec} \qquad (3)$$

where ν_{max} is the frequency of the maximum of the absorption band (*4*).

In addition to coloration by X or gamma rays, *F*-centers may be produced by: (*a*) heating the crystal in the alkali vapor; (*b*) injecting electrons electrolytically from a pointed cathode in contact with a heated crystal; (*c*) exposing the crystal to ultraviolet light in the long wavelength foot of the fundamental absorption band; and (*d*) converting *U*-centers to *F*-centers in a crystal containing alkali hydride in solid solution.

The first process, known as additive coloration, consists of heating the crystal in the presence of alkali metal vapor, which diffuses through it rapidly at elevated temperatures. If the crystal is cooled suddenly, the alkali is retained in an atomic dispersion, whereas slow cooling leads to colloidal agglomerations of metal characterized by absorption bands of an entirely different color. If the additively colored crystal is reheated in vacuo, the color disappears and the alkali metal boils out of the crystal and condenses on the walls of the container. Dissolving an additively colored crystal in water yields an alkaline solution, also indicating a stoichiometric excess of metal atoms. The excess alkali atoms pro-

vide the surplus *F*-center electrons and positive ions.

The following process (*5*) has been proposed to describe the mechanism of *F*-center formation. An alkali atom must first be adsorbed on the surface of the crystal. It there loses its valence electron to the conduction band, leaving the positive ion on the surface. A negative ion can then move out of the underlying layer to a position adjacent to the positive ion. At elevated temperatures, the vacant lattice point migrates into the interior of the crystal where it eventually traps a conduction electron to form an *F*-center.

The electrolytic method of coloration may also be considered an additive process. Electrons are injected into the crystal at the cathode, while halogen ions are simultaneously driven out at the anode. The crystal is usually placed on a flat plate which serves as the anode and contacted on the opposite face with a pointed cathode. This assembly is heated in an oven while a potential difference of several hundred volts is applied across the electrodes. A cloud of *F*-centers is then observed to expand out of the cathode. If the field is reversed, the cloud withdraws to the electrode from which it came.

All of the properties of a crystal related to a stoichiometric excess of metal atoms are influenced by structure. If the crystal is processed in such a way as to provide a great many defects, the number of alkali atoms that can be taken up is correspondingly increased. Sublimed salt layers, for example, may have 1,000 times as many internal defects per unit volume as has well-crystallized salt. Similarly, materials which have been crystallized by sudden cooling or have been grown very rapidly show increases in numbers of defects per unit volume. Any previous history of thermal or mechanical treatment influences the number of alkali atoms that can be absorbed by the lattice.

Thermal Bleaching of *F*-centers

Soft crystals, such as the heavier alkali metal bromides and iodides, are more difficult to color near room temperature and lose their color more rapidly than the lighter alkali metal chlorides and fluorides which color readily and retain their color for a longer time. Thermal bleaching is, of course, accelerated at higher temperatures.

With the formation of an *F*-center absorption band by irradiation with X-rays, a new band appears simultaneously in the ultraviolet. The area under this so-called *V*-band is equal to that of the *F*-band, indicating equivalence of the numbers of *F* and *V* centers.

In NaCl, KCl, and KBr, the *V*-band maximum appears at a frequency approximately 2.4 times that of the *F*-band. Temperature changes affect both bands in the same way, reducing the width and shifting the peak to shorter wavelength as the temperature is lowered.

These similarities between the *F* and *V*-bands make it appear that the *V*-center is the positive analog of the *F*-center, a positive hole trapped at a vacant cation site.

The processes of coloring and bleaching involve the following steps: (1) irradiation releases electrons from halogen ions; (2) the electrons diffuse through the lattice until trapped at vacant anion sites, forming *F*-centers; (3) the remaining neutral halogen ions constitute positive holes which combine with alkali ion vacancies to form *V*-centers; (4) thermal excitation releases the electron from the *F*-center whence it travels through the lattice until it finds a halogen atom at a *V*-center; and (5) recombination of the electron with the *V*-center reproduces the original halogen ion and restores the colorless condition of the crystal.

No thermal bleaching is observed in additively colored crystals, because the introduction of an excess electron or alkali atom leaves no positive hole with which the *F*-center may subsequently recombine.

The stability of coloration of X-rayed NaCl, LiF, and KBr at room temperature was studied by Alger (*3*) using crystals that had received exposures varying from 10^4 to 10^7 r. The initial rate of decay of *F*-centers increased with the number originally formed, and the shape of the decay curve was roughly exponential. An explanation of the thermal decay process was presented to show that a simple exponential could not express the decay versus time.

According to this theory, the electron released thermally from the *F*-center has the possibility of being captured by a vacancy to form a new *F*-center or to become attached to a neutral halogen atom at a *V*-center. In the latter case, the number of *F*-centers is reduced by one and the ionized *F*-center becomes a lattice vacancy. The bleaching process progressively increases the ratio of lattice vacancies to positive holes, thereby increasing the probability that a thermally released *F*-center electron will again be captured to form a new *F*-center. The lower the density of *F*-centers, therefore, the slower thermal bleaching proceeds.

Many recent studies have demonstrated that the bleaching process is more involved than is indicated in the foregoing explanation. Although bleaching may be proportional to the product of number of *F*-centers and positive holes, other factors influence the decay rate (*6*).

From the standpoint of the utilization of X-ray-induced *F*-center coloration in alkali halides for dosimetry, it is quite clear that the thermal bleaching rate in KCl and KBr is too rapid to permit their use as dosimeters. The half-life of the color in KBr, for example, is measured in seconds. In NaCl, with a half-life of the order of weeks, the rate is sufficiently slower to permit the use of this crystal with perhaps a suitable correction for elapsed time between exposure and measurement. In LiF, Alger found a half-life for decay of color of almost a year, but the *F*-band is in the ultraviolet, and the observed visible color is due to a subsidiary band of very much weaker intensity.

U-Centers

Thermal fading of *F*-center coloration at moderate temperatures may be minimized if the crystal is saturated with *U*-centers before exposure to radiation. A crystal containing *U*-centers is still completely transparent in the visible spectrum, but is characterized by an absorption band in the ultraviolet lying on the long wavelength side of the fundamental absorption. See the example of this for NaCl in Fig. 1. Absorption of ultraviolet or X-rays within the *U*-band transforms *U*-centers into stable *F*-centers at room temperature.

Although descriptions of *U*-bands produced by several different techniques had appeared earlier in the literature, it was not established until 1936 by Hilsch and Pohl (*7*) that

U-centers were associated with alkali hydride in solid solution in an alkali halide crystal.

It then became apparent that a high concentration of U-centers could be obtained by heating a crystal, additively colored with a stoichiometric excess of alkali, in an atmosphere of hydrogen until it was thoroughly bleached. The hydrogen diffuses rapidly into the crystal at elevated temperatures. X-ray measurements of the lattice constant of KBr containing KH proved that the hydride entered into solid solution up to concentrations of 1.5 mol per cent, with hydrogen ions substituting for negative bromine ions in the lattice.

Like the F-bands, the spectral location of the U-bands of the various alkali halide crystals is dependent only on the interionic distances. It can be calculated from the formula (*8*)

$$\lambda_{max} = 615\ d^{1.10}\ \text{Ångstroms} \quad (4)$$

where d is the interionic distance.

By analogy with the electron transition responsible for the fundamental absorption band, the U-band absorption must involve a transition of an electron from the hydrogen ion to the surrounding metal ions. The displacement of the U-band to the long wavelength side of the fundamental band is equivalent to the difference in electron affinity between hydrogen and bromine.

As is the case for absorption of light in the fundamental bands, no photoconductivity is observed with irradiation in the U-band.

The mechanism of the production of F-centers from U-centers has been described (*5*) as follows: An electron is removed from a hydrogen ion to an excited state in the neighborhood of the surrounding alkali ions. If the remaining neutral hydrogen atom diffuses away before the electron can recombine with it, a vacant lattice point is left in which the electron is subsequently trapped to form an F-center.

At higher temperatures, the quantum yield of the conversion of U to F-centers should increase, since the hydrogen atom can diffuse away more readily. Irradiating a crystal with ultraviolet light in the U-band, Hilsch and Pohl measured a quantum yield of close to 100% at 500° C in KBr. At room temperature, the yield dropped to 25%. Similar tests with gamma rays indicate a much smaller temperature dependence of the yield. For practical purposes, the efficiency of coloration by roentgen dosage may be considered constant over a range of ±20° C about room temperature.

The thermal stability of the U-F center transition in KBr was also described by Hilsch (*9*) in terms of

$$N_F/N_U = A\ e^{-1.1ev/KT} \quad (5)$$

where N_F and N_U are the numbers of F and U-centers, respectively, A is a constant of the crystal, K is the Boltzmann constant, and T is the absolute temperature. This equation expresses the thermal equilibrium between U and F-centers at any temperature. If the equilibrium is upset by illuminating the crystal with a flash of ultraviolet light in the U-band, the time required to return to equilibrium may be measured. Hilsch found that at 625° C, the newly formed F-centers decayed to half their initial number in 2 seconds; at 375° C, the half-life increased to 90 seconds. At room temperature the return to equilibrium is so sluggish that the F-centers in KBr may be considered essentially permanent.

Sensitizing KBr

The experimental technique used to introduce a high concentration of U-centers into KBr crystals is a two-step procedure and is outlined at the top of this page. It is a treatment of additive coloration followed by hydrogenation that is capable of introducing uniform U-center concentrations as high as 2×10^{18} per cm³ in a KBr crystal with a minimum dimension of 1 cm.

Similar results, which are close to the theoretically expected maximum density of F or U-centers, are obtained with KCl. Little information is available on other alkali halides which require processing at higher temperatures. It is interesting to note that concentrations of 10^{22} F-centers per cm³ have been introduced electrolytically in fluorite crystals (*10*).

Figure 2 shows a series of spectrophotometer traces of the F-band produced by irradiating a U-center crystal of KBr, 5-mm thick, with successive 100-r doses of 1-Mev gamma rays. A 50-r dose in a crystal 1-cm thick should be readily detectable by the unaided eye. This represents a somewhat higher sensitivity than is obtained in an untreated crystal even before any thermal bleaching occurs.

The accuracy with which color intensity matching may be carried out can most probably be increased by the use of auxiliary viewing devices. Any method of increasing the path length of the light viewed through the crystal will increase the sensitivity

Procedure for Sensitizing KBr

1 Additive coloration. To color the crystals additively, seal them in a Pyrex glass tube connected to an evacuation system. After exhausting the air, distill the potassium metal into the glass container. Seal off the container and heat it in an oven at about 1,140° F for several hours. At this temperature, the glass softens sufficiently to collapse under external atmospheric pressure. (To resist collapse of the softened glass, the tube may be fitted internally with an alundum sleeve, or an inert gas such as helium may be introduced at atmospheric pressure.) Then cool the Pyrex capsule rapidly. A cold air blast may be applied to reduce the temperature from 1,000° F to room temperature in a few minutes. In breaking the container to remove the crystals, observe the usual precautions in handling alkali metal. Any metallic potassium remaining on the crystal faces can be removed by scraping. The crystals at this stage are so densely colored, even in the wings of the F-band that the entire spectrum of visible light is almost totally absorbed, and they appear black rather than blue.

2 Hydrogenation. Seal the crystals into another Pyrex tube provided with connections for flowing hydrogen over the heated crystals. Heat the unit in an oven to about 1,000° F. Burn off any excess hydrogen at the exit of the tube and continue the heating until the crystals are bleached.

of detection proportionately. A preferred geometrical form would be a rod that is long compared to its width. Coating the back and side surfaces so as to reflect light internally is a simple means of doubling the optical path. If the size of the crystal permits, multiple internal reflections may be produced before viewing. It is helpful to view the coloration through a filter of a color that is complementary to that of the crystal, such as a Wratten No. 26 filter for use with KBr.

Dog-tag Dosimeters

Effective medical treatment of large numbers of casualties in the aftermath of an atomic bombing could be facilitated if everyone were equipped with a simple "dog-tag" dosimeter.

Although symptoms of radiation sickness develop clearly enough within a few days so that victims may be broadly grouped according to exposures of 0–200 r, 200–400 r, 400–600 r, the complications introduced by flash burns and blast injuries make difficult any diagnosis of gamma-ray damage apart from other injuries. It is desirable therefore to have an independent roentgen-dose measurement immediately available to segregate casualties according to dosage within limits of roughly 100 r.

The final embodiment of a colorimetric crystal dosimeter may be a small plastic case containing the sensitized crystal surrounded by its comparison scale. For example, the crystal may be a rod about one cm long and a few mm thick encased in a closely fitted concentric plastic cylinder of equivalent thickness. The viewing end of the outer cylinder would be divided into four sectors covered with colored strips of translucent material corresponding to doses of perhaps 100, 200, 400, and 600 r. The sensitive crystal would be viewed in conjunction with the adjacent colored sectors and the dose would be read by matching the intensity of its color to one of the four sectors. For convenience, the entire unit could be worn as a locket hanging from the neck on a light chain.

If the dosimeter must cover a wide range of gamma-ray wavelengths, its response relative to an air ionization chamber will vary in different parts of the spectrum. The lower the atomic weight of the crystal, the less marked the differences will be. In a crystal such as KBr, the response to roentgen dose peaks sharply in the 100–200 kev region because of the enhanced photoelectric absorption relative to air.

This excessive sensitivity to soft radiation may be adequately minimized by encasing the dosimeter in a relatively thin sheet of absorbing material. If lead is used, the thickness need not exceed one millimeter.

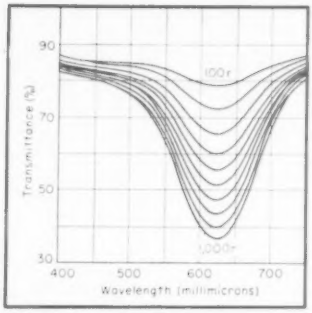

FIG. 2. Spectrophotometer traces of the *F*-band in a 5-mm thickness of KBr saturated with *U*-centers after successive exposures to 100-r doses of 1-Mev gamma rays

Photoconductivity, Luminescence

Practical interest in alkali halides as dosimeters has been concentrated primarily on the colorimetric aspects, but dosage energy stored in a crystal containing *F*-centers may also be released in photoconduction and luminescence. These phenomena provide much more sensitive dose indications than the *F*-center coloration, but auxiliary measuring equipment is required.

In the process of stimulating the photocurrent or luminescence, the centers in which the phenomena originate are wiped out. This is in contrast to the permanent indication offered by a colorimetric dosimeter, and to the stable luminescence developed in a radiophotoluminescent system such as the recently developed Ag-activated phosphate glass dosimeter (*11*). In it, ionic Ag is reduced to atomic Ag by X-ray irradiation, producing permanent luminescent centers. Excitation of the glass with near ultraviolet light releases a visible orange glow proportional to the dosage absorbed.

Bleaching. In the discussion of fading of *F*-center coloration, mention was made of only the thermal bleaching effect. Illumination with visible light is similarly effective in bleaching the *F*-coloration. Simultaneously with bleaching, a current will flow if voltage is applied to the crystal.

The model proposed for thermal bleaching applies equally well to optical bleaching. Electrons released by X-rays are trapped at halogen ion vacancies to form *F*-centers. Absorption of light by the *F*-centers frees the trapped electrons and, in the absence of an applied field, they diffuse through the crystal until they meet positive holes (*V*-centers) with which they recombine, or until trapped in negative ion vacancies to form new color centers.

If voltage is applied to the crystal during the bleaching process, the electrons released from *F*-centers acquire a drift velocity in the direction of the electric field and give rise to a measurable current. The charge transferred by this current is proportional to the number of *F*-centers destroyed by the bleaching light and therefore to the original X-ray dose.

Photoconductivity. In the photoconductive process, practically no electrons leave the crystal. The number of color centers formed at low dosage levels is small compared to the total number of traps available in the crystal. Of all the electrons released from *F*-centers by absorption of light, a very small fraction are recaptured by the same traps. The great majority drift until caught by new traps to form *F*-centers again.

Associated with the average drift velocity in the electric field is a mean displacement range. The charge induced on the electrodes per electron released from an *F*-center is the product of the charge of the electron and this mean displacement per cm of crystal. For KBr, a typical displacement-range value is about 10^{-7} cm per volt per cm of KBr. If 1 mr of gamma rays produces of the order of 10^9 *F*-centers in a cm^3 of KBr, a potential difference of 1,000 volts would produce an external flow of $10^{-7} \times 10^3 \times 10^9 = 10^5$ electronic charges, or 5×10^{-14} coulombs, to the electrodes. A charge of this magnitude is readily measurable with electrometer circuits. It is apparent, therefore, that a photoconductive alkali halide dosimeter, 1 cm^3 in volume, is capable of indicating dosage at levels several orders of magnitude below the visible threshold of *F*-center coloration.

In practice, it is desirable to bleach the crystal completely with a flash of

light, preferably shorter than one second in duration, so as to deliver a large voltage pulse to the electrometer tube without requiring excessively high resistance in the input circuit. Sufficient intensity of light is available from a small incandescent bulb to discharge virtually all the *F*-centers in KBr in a fraction of a second.

Thermal bleaching is not a serious disadvantage in a photoconductive dosimeter if it is used at low dosage levels, since the rate of thermal bleaching decreases as the number of *F*-centers per cm^3 decreases. The photoconductivity, however, is very sensitive to crystal perfection, and individual specimens of the same type of crystal may produce widely different indications for the same dose. At higher dosage levels, the thermal bleaching effect would cause a decrease in stored photoconductivity exactly paralleling the color center loss with elapsed time.

Luminescence. A visible red luminescence in pure LiF following X-ray exposure was first observed by Molnar (*12*) and is the basis of a thermoluminescent dosimeter developed by Daniels (*13*). Radiophotoluminescence in the visible region has also been observed in NaCl-Ag and other silver-activated alkali halides (*11*). The most remarkable luminescent properties of the alkali halides, however, are associated with emission spectra in the ultraviolet.

In addition to the prompt fluorescent scintillations observed during bombardment of an alkali-halide crystal with alpha particles, X-rays, or gamma rays, four types of ultraviolet luminescence may be released long after the exposure if any *F*-center coloration is still retained. These are: (1) phosphorescence, (2) fluorescence accompanying exposure to visible light in the *F*-band, (3) thermoluminescence, and (4) triboluminescence induced by mechanical deformation.

The spectral distribution of ultraviolet luminescence is the same for all four processes and is determined only by the energy of recombination of the electron released from an *F*-center with a positive hole at a *V*-center.

Ultraviolet luminescence in relatively pure crystals was described by Glasser and Beasley (*14*), who measured the emission with photon counters (*15*). Addition of impurities, such as Ag, Cu, Ni, Mn, Pb, enhances the ultraviolet luminescence very markedly

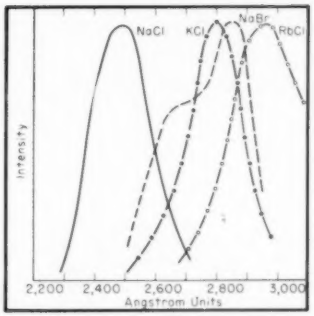

FIG. 3. Ultraviolet luminescence spectra of Ag-activated alkali halides. The intensity scale is arbitrarily adjusted for each curve, depending on the crystal used

without altering the spectral distribution. Silver, in particular, increases the intensity of ultraviolet emission in NaCl and KCl by factors of 100 to 1,000, compared to crystals of high purity. NaCl containing approximately one mol per cent of Ag, fluoresces under gamma irradiation almost as efficiently as the organic scintillation crystals commonly used with photomultipliers. Figure 3 illustrates the ultraviolet luminescence spectra of several alkali halides as measured by Polonsky (*16*), who investigated the remarkable sensitizing effect of Ag.

After photochemical coloration by X-rays, a crystal of NaCl-Ag held in the dark at room temperature may continue to emit phosphorescent ultraviolet light for minutes, hours, or days, depending on the dose absorbed. The *F*-center coloration bleaches simultaneously, but after phosphorescence has decayed to a level too low to measure, some *F*-center coloration will still remain. Illumination of the crystal with visible blue light in the *F*-band then produces a strong ultraviolet fluorescence. This visible-light-stimulated fluorescence persists until the *F*-center coloration is completely bleached.

Heating the colored crystal to temperatures above about 150° C produces a thermoluminescence closely resembling the visible-light-stimulated fluorescence. At least two peaks are observed in the thermal emission as the temperature is raised continuously from room temperature to red heat. Plastic deformation produces the same spectrum of ultraviolet luminescence with the total emission depending on the initial concentration of *F*-centers and the amount of stress applied.

The ultraviolet luminescence of the alkali halides has received particular attention in connection with the use of the crystals in combination with photon counter tubes or scintillation detectors. In the spectral region below 3,000 Å, it is possible to produce photon counter yields of the order of 10^{-2} to 10^{-4} counts per photon, yet the response to visible light may be almost completely negligible. It is therefore possible to measure the ultraviolet luminescence of a rock salt crystal placed before the quartz window of an ultraviolet photon counter while exposing the crystal to the bleaching action of visible light.

Of the four types of luminescence, thermoluminescence appears to be the most readily adaptable to dosimetry. The equivalent of a few mm^3 of the crystal or a fraction of a gram of powdered NaCl-Ag is sufficient to provide easily measurable ultraviolet intensities for doses of the order of 0.1 r. A convenient arrangement consists of a wire gauze coated with the powdered material. The gauze may be heated by passing a current through it. Then the thermoluminescence is measured with a photon counter in close proximity to the gauze. The total ultraviolet photon count registered during the discharge of thermoluminescence is proportional to dose.

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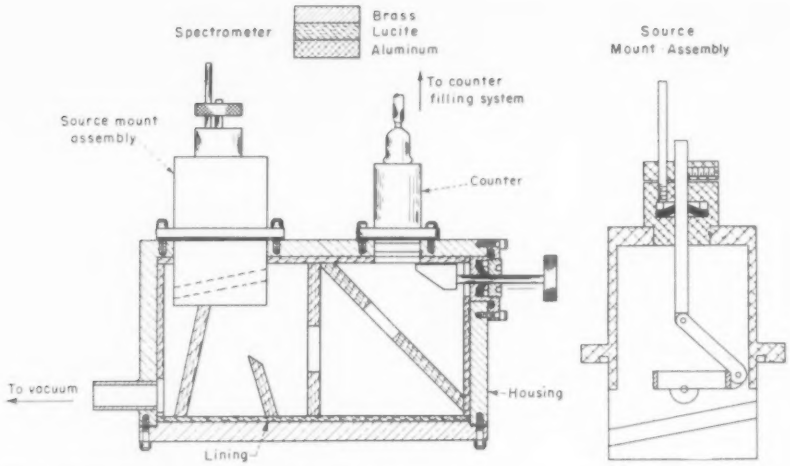

FIG. 1. Design details of uniform magnetic field beta-ray spectrometer

Interaction of Phosphorus-32 Beta Rays with Matter

The energy distribution of beta rays from a thin P^{32} source mounted on collodion film has been measured before and after addition of various absorbers and backscatterers. The angular distribution has also been determined

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INTERACTIONS of monoenergetic electrons with thin layers of absorbing materials have been investigated experimentally and are reasonably well described by theoretical expressions. The primary interactions of electrons with matter are elastic scattering by nuclei, and ionization.

The scattering of beta rays is described approximately by the Rutherford theory of scattering (*1*), and by the Mott theory formulated on the basis of quantum mechanics (*2*). Recent measurements by Cox and Chase (*3*) and by Buechner *et al.* (*4*) have given excellent experimental confirmation of the Mott single-scattering equation. The present theory of ionization by fast electrons was formulated by Bohr (*5*) and refined by Bethe (*6*) and Bloch (*7*).

The problem of applying these

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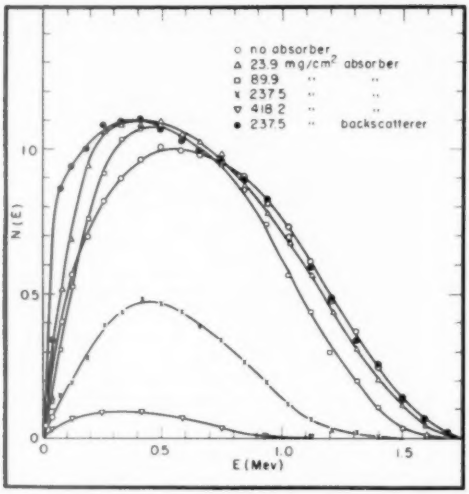

FIG. 2. Effect of Lucite on the energy spectra of P^{32} beta rays at an angle of 0°

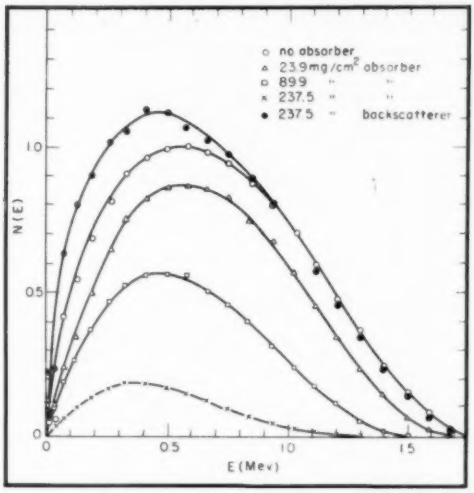

FIG. 3. Effect of Lucite on the energy spectra of P^{32} beta rays at an angle of 70°

fundamental equations to the interaction of a continuous energy distribution of beta rays is complicated by the fact that multiple scattering must be considered, and by the fact that the energy distribution may be a function of absorber thickness. This paper describes an investigation of the problem on an experimental basis, having as one of its aims the derivation of simplifying assumptions which will facilitate theoretical description of interactions of continuous beta rays with matter.

Apparatus

A 180° uniform-magnetic-field spectrometer was used in the spectra determinations. The design followed those of Lawson and Tyler (*8*), Neary (*9*), Langer and Cook (*10*), and O'Conor (*11*), with the following special features:

1. Absorbers of various thicknesses may be placed in front of the source, and backscatterers may be placed behind the source.

2. The source, absorbers, and backscatterers may be rotated as a unit through an angle of from 0° to 70°, measured from the normal to the source and the line of observation.

3. The source unit may readily be removed to change the source, absorber, or backscatterer.

Figure 1 shows the spectrometer design.

A proportional counter operated at 20 cm of *n*-butane, and with a window made of a 0.5-mg/cm² sheet of Nylon was used as the detector. The calculated momentum resolution for the spectrometer was 3.9%.

The geometrical arrangement desired in this investigation is that of plane sources, absorbers, and backscatterers of infinite area. This geometry is, of course, impossible to reproduce in a spectrometer source, but an equivalent geometry is available. If a finite plane source is employed, and all the radiation leaving the surface of the absorber is observed, the characteristics of the total radiation will be identical to those of the radiation leaving a prescribed area on the surface of a plane absorber and source of infinite area. In the first case, radiation leaving the absorber at points not directly above the source compensates for the radiation in the second case leaving the prescribed area on the absorber and originating from points on the source not directly beneath the prescribed area. This requirement imposes an additional consideration in that collimating slits may not be close to the source and absorber unit.

The uniform magnetic field was provided by an Armco-steel electromagnet. Continuous record of the magnetic field was maintained by a rotating spool of wire connected through slip-rings to a Ballantine electronic voltmeter. The actual conversion factor was obtained by observation of the endpoint of the P^{32} spectra, combined with the assumed maximum energy of 1.70 Mev. This is the average of the 1.689 ± 0.01-Mev value of Langer and Price (*12*), and the 1.712 ± 0.008-Mev value of Siegbahn (*13*).

The source was mounted on a thin collodion film of from 20 to 30 μg/cm², formed on a loop of fine phosphor-bronze wire. Various methods were attempted to form a uniform, thin layer of P^{32} on the film. Evaporation would have been the ideal method, but because of the large amount of activity desired, about 1 mc of P^{32}, this method was not considered feasible. Drying the phosphoric acid directly and with the addition of a small amount of gelatin proved unsatisfactory. In certain cases, the deposit appeared uniform, but autoradiographs showed the activity to be located at one point on the mount.

The method used was the precipitation of barium hypophosphate by the addition of an appropriate amount of barium chloride to the phosphoric acid on the film, and drying in vacuum. The source area of 0.3 cm² was defined by placing fine threads of dried cement on the film before addition of the solutions. The weight of the source

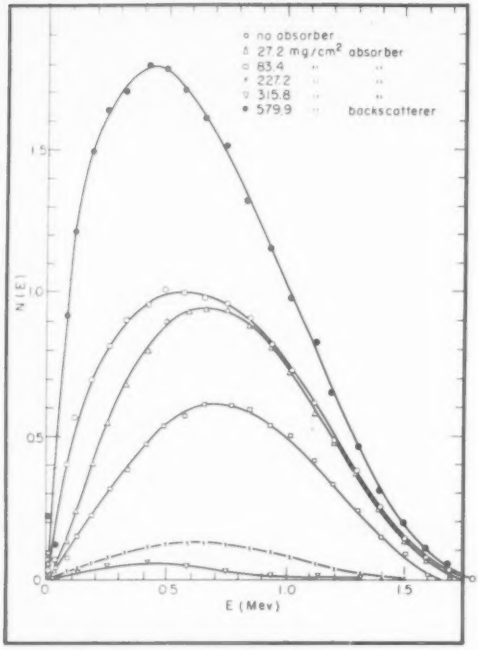

FIG. 4. Effect of platinum on the energy spectra of P^{32} beta rays at an angle of 0°

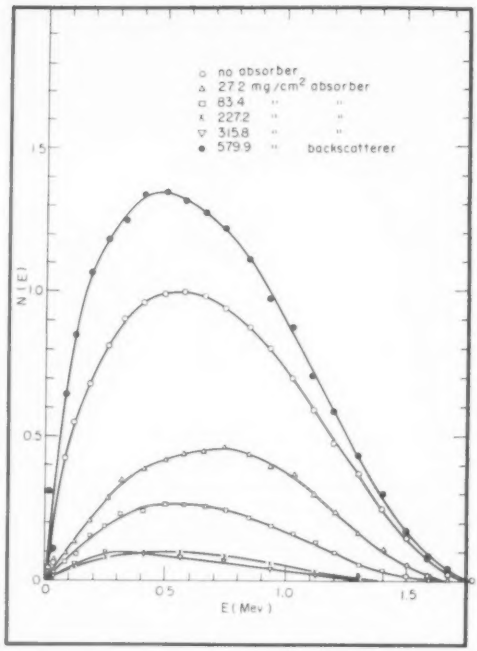

FIG. 5. Effect of platinum on the energy spectra of P^{32} beta rays at an angle of 70°

was about 0.1 mg and was determined both by the concentrations of the chemicals and by direct weighing. Only sources whose autoradiographs showed uniform deposition of activity were used.

An evacuated tube was used to determine the angular distribution of the beta rays from the source or absorbers. The source assembly and counter were the same as those used with the spectrometer. The vacuum chamber was lined with Lucite coated with Aquadag, and a Lucite aperture was located at the center to minimize scattering from the walls.

Experimental Results

The effect of Lucite absorbers and backscatterers is shown in Figs. 2 and 3, which show the observed spectra viewed from 0° and 70° to the normal of the source. A small correction has been applied to the data to correct for window absorption and scattering from the source frame so that the spectrum with no absorber or backscatterer agrees with the calculated Fermi spectrum for 1.70 Mev maximum energy. This correction is justified primarily because of its small magnitude and its negligible effect on the over-all shape of the spectra. The average energy of the spectra before applying the correction was 0.694 Mev, while the average energy of the calculated Fermi spectrum was 0.697 Mev.

The effect of small thicknesses of Lucite absorber is to decrease the number of high-energy beta rays at all angles, while the low-energy beta rays are removed from the large-angle spectrum and are added to the normal spectrum. At larger thicknesses of Lucite absorber, this effect is no longer apparent, although the number of beta rays transmitted at 70° is considerably less than that at 0°. The spectrum of a thin source with an essentially thick backing of Lucite is relatively insensitive to angle of observation, although there is a tendency for more beta rays of low energy to be scattered in the forward direction.

Figures 4 and 5 show the effect of platinum absorbers and backscatterers on the P^{32} spectra. In this case, the first effect of absorption is to decrease the number of low-energy beta rays transmitted at all angles. The spectra at large angles from the normal are uniformly attenuated much more than those at normal incidence. The backscatterer throws radiation predominantly into the forward direction, although all energies of β-rays are scattered approximately the same degree.

The effect on the spectra of absorption may be observed much more quantitatively by plotting the average energy of the observed spectra as a function of absorber thickness and of angle. Figure 6 shows such plots for Lucite, aluminum, copper, tin, and platinum absorbers.

The effect of small amounts of added absorber is particularly apparent with the Lucite and aluminum plots since a number of absorbers of small thickness were used. Very small amounts of absorber decrease the average energy of the radiation in the forward direction by scattering soft radiation from large angles into the forward direction. At about 20 mg/cm², this effect becomes saturated for soft beta rays, but the more energetic

beta rays continue this process, with the result that the average energy of the spectrum at small angles increases above that at large angles. At about 90 mg/cm² for Lucite and 80 mg/cm² for aluminum, this effect, in turn, becomes saturated, and the relative change in the average energy beyond this point is negligible. However, all curves decrease about 10% per 100 mg/cm², which is approximately the half-thickness for absorption by materials of low atomic number.

The curves for copper, tin, and platinum show the same effects, although the equilibrium is reached at smaller values of absorber thickness. Figure 7 shows the average energy of the backscattered radiation as a function of the atomic number of the backscatterer and of angle. The average energy rises rapidly up to atomic number ~ 25, and then increases more slowly.

Figures 8–12 show the angular distribution of the radiation transmitted and reflected by Lucite, aluminum, copper, tin, and platinum. The angular distribution of the radiation leaving the source or absorber, $N(\theta)$, is defined as the number of beta rays crossing unit area on the surface and entering a unit solid angle at the angle θ from the normal. The angular distribution of radiation within a thick source can readily be shown to have a $\cos\theta$ dependence with respect to an arbitrary plane located within the source.

Figure 13 shows two intersecting planes of equal area, ΔS, located within a thick source. The planes intersect at an angle θ, and the normal intensities to the two planes, $N(\theta = 0)_1$ and $N(\theta = 0)_2$, are shown. These are, of course, equal since all directions are equivalent within the source. The number of particles crossing plane 2 at an angle θ, $\Delta S_2 N(\theta = \theta)_2$, is not equal to $\Delta S_1 N(\theta = 0)_1$ since only a portion of this radiation crosses ΔS_2. The radiation crossing the shaded area of ΔS normally will not enter $\Delta S_2 \times N(\theta = \theta)_2$. Therefore, one can write

$$\Delta S_2 N(\theta = \theta)_2 = \Delta S_1 N(\theta = 0)_1 (1 - u)$$

where u is the shaded fraction of ΔS. Since ΔS_2 equals ΔS_1, one can write, from trigonometric relations,

$$N(\theta = \theta)_2 = N(\theta = 0)_1 \cos\theta = N(\theta = 0)_2 \cos\theta$$

Thus, radiation crossing the arbitrary plane 2 follows a $\cos\theta$ dependence. Scattering of beta rays will not affect the validity of the derivation since ΔS may be taken as small as desired.

The angular distribution of radiation leaving the surface of a thick source or, as in the present case, leaving the surface of a thick absorber, will not, in general, exactly follow the $\cos\theta$ dependence because the surface will interact on the radiation crossing it. The transition of the radiation from the constant angular distribution approximating that of the thin source, $N(\theta) = \text{constant}$, to an angular distribution approximating that of $\cos\theta$ is most clearly demonstrated in the curves for Lucite and aluminum. With Lucite, the equilibrium angular distribution has been nearly reached with the 89.9-mg/cm² absorber, while for aluminum the equilibrium thickness can be definitely stated as being between 66.6 and 140 mg/cm². The equilibrium thickness decreases with increasing atomic number of the absorber, so that for platinum it has been attained with the 27.2-mg/cm² absorber.

The angular distribution of the backscattered radiation is nearly isotropic [$N(\theta) = \text{constant}$] for Lucite, but approaches a distribution similar to that of $\cos\theta$ for backscatterers of higher atomic number. The intensity of the backscattered radiation increases markedly with increasing atomic number.

Conclusions

The average-energy curves of Fig. 9 can be considered to be the result of two phenomena. The scattering of radiation first results in a marked drop in the average energy of radiation emitted in the forward direction; as the absorber thickness is increased, the process is reversed as more energetic radiation is scattered into the forward direction. The second phenomenon is a gradual decrease in the average energy of all radiation leaving absorbers of low atomic number, and an actual increase in the average energy of all radiation leaving the higher atomic number absorbers as the absorber thickness is increased.

The scattering effects are remarkably consistent with the observed changes in the angular distribution. In general, when the rapid changes in the average energy that result from scattering are no longer apparent, the angular distribution has approached an equilibrium form. These two observations would strongly suggest that over a

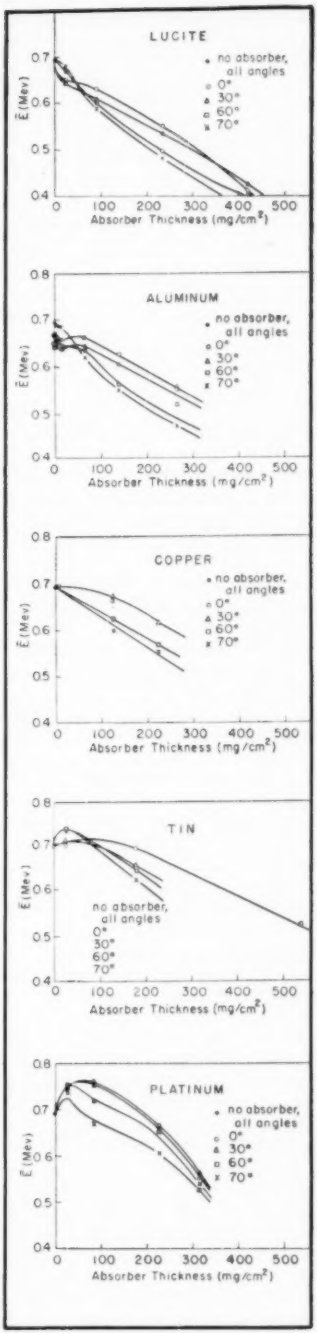

FIG. 6. Average energy of observed spectra for various absorbers

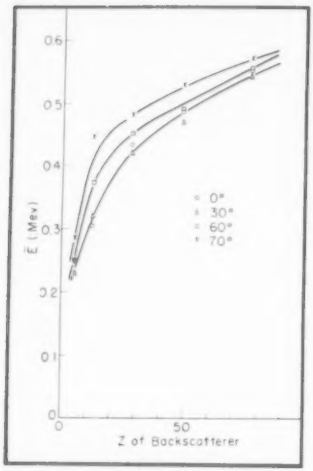

FIG. 7. Average energy of backscattered P^{32} beta rays for various angles of observation

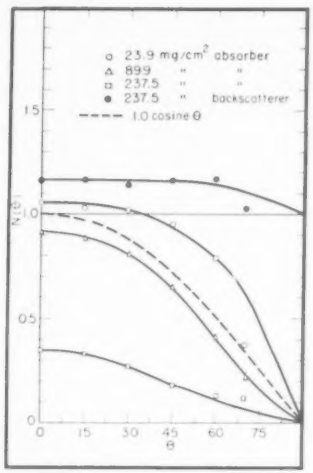

FIG. 8. Angular distribution of the P^{32} β-rays transmitted and reflected by Lucite

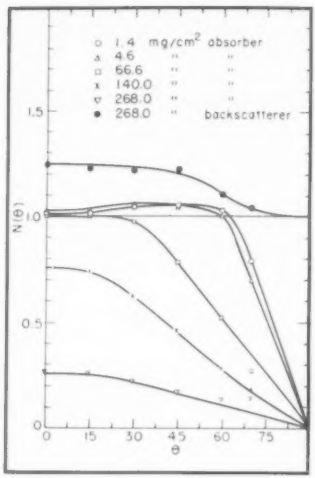

FIG. 9. Angular distribution of the P^{32} β-rays transmitted and reflected by aluminum

considerable range of absorber thickness, the interaction of beta rays with matter can be considered a diffusion process in which the average energy of radiation remains relatively constant and the angular distribution of the radiation is random. This would appear to be a good approximation for absorber thicknesses greater than one half-thickness for low-atomic-number absorbers, and of somewhat less than a half-thickness for high-atomic-number absorbers. It is interesting that Fournier and Guillot (*14*), in 1933, undertook to explain the exponential character of beta-ray absorption by assuming that the energy spectrum remained essentially constant.

One observation is not directly explained by this assumption. The average energy of the transmitted radiation for absorber thicknesses in the diffusion range is not the same for all angles of observation. This can be explained by the fact that the interaction of the surface on the equilibrium angular distribution of the radiation crossing the surface may itself be energy dependent, resulting in different spectra and different average energy as the angle from the normal is varied.

The conclusion that the interaction of beta rays with matter may be considered, under certain conditions, to be represented by a diffusion process, has been drawn solely on the experimental data. The application of a diffusion theory to the general problem of counting and radiation dosage determination will be presented in another paper. However, it would be interesting to compare this conclusion with the theory of diffusion processes. The theory of multiple scattering has been developed by Williams (*15*), and its application to the interaction of the soft component of cosmic radiation with matter has been discussed by Rossi and Greisen (*16*). The average angle through which a beam of radiation is scattered in traversing a distance t is $\sqrt{\overline{(\theta^2)}_X}$, where

$$\overline{(\theta^2)}_X = \frac{1}{2}\left(\frac{21}{p\beta c}\right)^2 t$$

where p is the momentum of the particles (electrons, in the present case), βc is the velocity, and t is the absorber thickness expressed in radiation lengths. The radiation length, X_0, is defined by

$$\frac{1}{X_0} = 4\alpha \frac{N}{A} Z^2 r_0^2 \log 183\ Z^{-\frac{1}{3}}$$

In this equation, α is the fine structure constant ($\frac{1}{137}$), N is Avogadro's number, A is the atomic weight, r_0 is the Bohr radius, and Z is the atomic number of the absorbing material. The equation for multiple scattering holds rigorously for small angles only, but the fairly gross assumption will be made that an average angle of scattering of $\pi/2$ indicates a random distribution of radiation in the absorber.

For radiation of energy 0.698 Mev (the average energy of the P^{32} spectrum), the absorber thickness, t, necessary to produce an average scattering angle of $\pi/2$ is calculated to be 2.89×10^{-3} radiation lengths.

Values of equilibrium absorber thickness, d_e, have been estimated from Figs. 6 and 8–12, and are presented in the table. These values can be estimated with reasonable accuracy for Lucite, aluminum, and platinum, but only approximate values can be obtained for tin and copper. From these values, the radiation lengths for the various materials have been computed and are presented in the table as the observed radiation length. The values calculated from the above equation are also presented for comparison. In view of the many assumptions, the agreement would seem to be somewhat fortuitous. But this agreement, together with the correct observed dependence on atomic number, indicates that the changes in the observed angular distribution and average energy for small absorber thickness may be explained on the basis of present theories of multiple scattering.

If the process for small absorber thicknesses is one of producing a random directional distribution of radiation, it would appear that a diffusion picture would describe the interaction of radiation with matter at distances from the source exceeding the

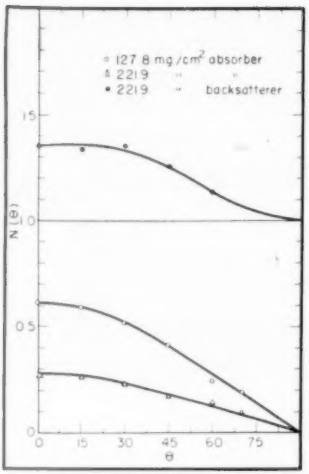

FIG. 10. Angular distribution of the P^{32} β-rays transmitted and reflected by copper

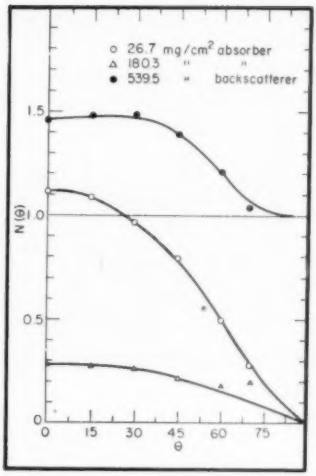

FIG. 11. Angular distribution of the P^{32} β-rays transmitted and reflected by tin

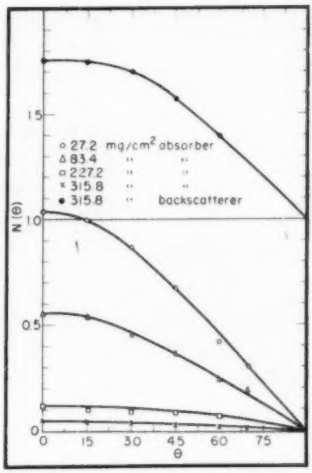

FIG. 12. Angular distribution of the P^{32} β-rays transmitted and reflected by platinum

equilibrium distance, or approximately a half-thickness. The relatively slow variation of average energy with absorber thickness might indicate that this change could be included in a diffusion theory as a correction rather than as a primary effect.

* * *

The author wishes to express his indebtedness to Professor R. D. Evans who suggested the problem and gave constant encouragement and advice. Valuable help and criticism have been offered by all of the members of the Radioactivity Center at M.I.T. Portions of the equipment were constructed in collaboration with Robert A. Dudley of this laboratory. This paper is a portion of a thesis submitted in partial fulfillment of the requirements for the degree Doctor of Philosophy at the Massachusetts Institute of Technology.

Observed and Calculated Radiation Lengths

Absorber	Z	d_e (mg/cm^2)	$X_0(obs.)$ (mg/cm^2)	$X_0(calc.)$ (mg/cm^2)
Lucite	6.24	90	31,000	49,000
Aluminum	13	80	27,000	26,300
Copper	29	50	17,000	13,000
Tin	50	20	6,900	8,900
Platinum	78	15	5,200	6,000

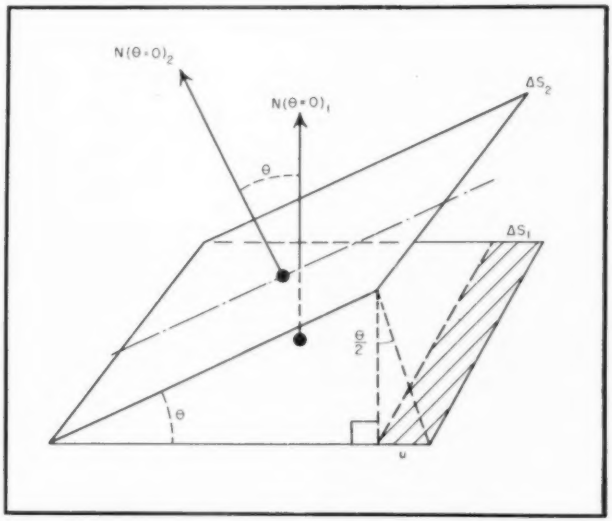

FIG. 13. Geometry for derivation of cos θ relation for radiation within a thick source

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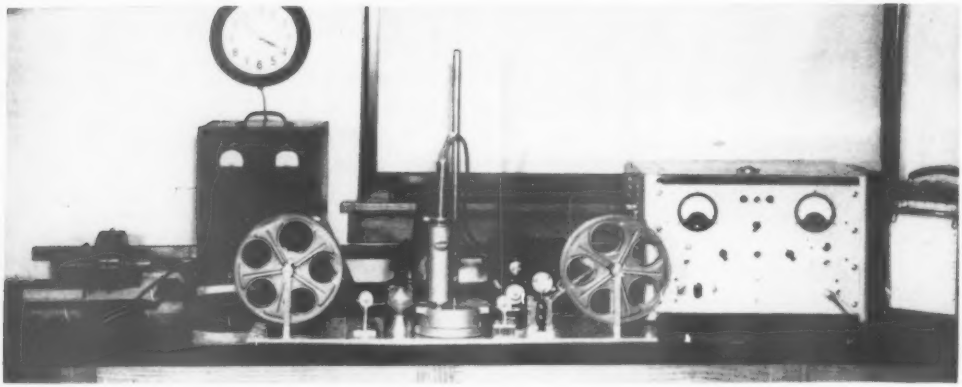

FIG. 1. The assembled monitor, showing supply reel, precipitator, detector, driving unit and take-up reel

A Monitor for Natural

For studies of the time variation of atmospheric radon and thoron products, a moving-tape monitor has been built. An electrostatic precipitator deposits aerosol samples on the tape which then passes under a counter

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THE PRESENCE in the atmosphere of minute quantities of natural radioactive substances became known soon after the discovery of the phenomenon of natural radioactivity (*1*). It has been shown that this material in the atmosphere owes its origin to uranium and thorium minerals distributed in the earth's crust. The radon and thoron gases formed in such minerals diffuse into the atmosphere where they decay and leave disintegration products which soon attach themselves to fine particulate matter in the air. Hence, an aerosol collection, which includes the very fine particles found in the atmosphere, possesses a small but measurable amount of natural radioactivity. This activity has been used to study the particle-size distribution of aerosols in the submicroscopic range (*2*).

In connection with this work, the need for a satisfactory monitor of the natural radioactivity in the atmosphere presented itself. The instrument to be described employs a moving metallic tape, and is designed to give a relatively high-level record of the activity due to natural substances in the atmosphere. The set-up of the monitor is shown in Fig. 1.

An apparatus that employs a moving filter paper has been described (*3*). It was designed primarily for measurement of long-lived contaminants in the atmosphere but, because of low collection and counting efficiencies, it yielded only a few counts per minute for the average alpha activity due to natural radioactivity.

Collection

The problem of monitoring the air for the natural radioactivity which it

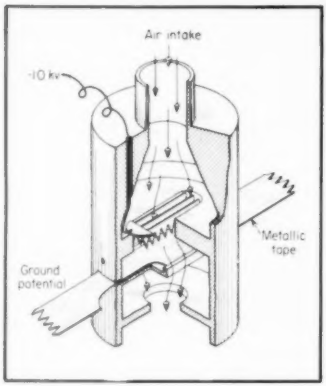

FIG. 2. The electrostatic precipitator

TABLE 1—Pertinent Parts of Uranium and Thorium Series

URANIUM			THORIUM		
	Half-life	*Energy (Mev)*		*Half-life*	*Energy (Mev)*
Uranium	4.55×10^9 y	4.21α	Thorium	1.34×10^{10} y	4.20α
Radium	1,600 y	4.79α	Thorium X	3.64 d	5.68α
Radon	3.825 d	5.49α	Thoron	54.5 s	6.28α
RaA	3.05 m	5.99α	ThA	0.158 s	6.77α
RaB	26.8 m	0.65β	ThB	10.6 h	0.36β
RaC	19.7 m	3.15β (99.96%)	ThC	60.5 m	2.20β (65%); 6.05α (35%)
RaC′	1.5×10^{-4} s	7.68α	ThC′	3×10^{-7} s	8.77α
RaD	22.2 y	0.025β	ThC″	3.1 m	1.82β
			ThD	Stable	

Atmospheric Radioactivity

contains is essentially one of collecting particulate matter from the atmosphere and presenting it in a sufficiently concentrated form for counting. The method wherein neutral particles are charged in a region of high current density, and subsequently precipitated in a strong electric field is known to be capable of removing very small suspended particles from an air sample with high efficiency. This feature of the electrostatic precipitator, as such a device is commonly called, makes it ideally suited for use in an air monitor since experiments have shown that about 90% of the natural radioactivity found on particulate matter in the atmosphere is attached to particles that have effective diameters less than 0.5 μ. Most of this fraction resides on particles in the size range 0.001–0.04 μ (*2*).

Another distinct advantage of the precipitator is that it can be designed to concentrate the particulate matter on a flat metallic surface. A much higher counting efficiency is attainable this way than with a mesh filter of the type used by Kuper *et al.* (*3*).

A cut-away view of the precipitator used in the monitor is shown in Fig. 2. Air enters at the top, flows down through a rectangular orifice that contains corona points, continues down to, and around, a metallic tape, and then passes out the exhaust tube. The air intake is connected to the out-of-doors by means of a length of flexible hose 1 in. in diameter which is ordinarily supported 0.8 meter above ground level. It is important that the air, which is drawn through the precipitator by an exhaust blower, is not processed at so great a rate that the efficiency of the precipitator for collection of fine particles is impaired. A rate of 0.03 m^3/min is normally used.

The corona points are cut from brass shim stock. They are ½ in. from the metallic tape, and are maintained at a potential of −10 kv with respect to the tape. During operation, the corona current is 0.35 ma. The tape is 0.001-in. aluminum, 1⅛ in. wide.

The Detector

The assembled monitoring equipment is shown in Fig. 1. The tape passes from the supply reel at left through the precipitator, under the detector, through rubber driving rollers, and on to the take-up reel. Ample tape is available for two weeks operation. It can be rewound, checked for long-lived background activity, and used again.

The driving unit for the 1-in.-diameter rubber rollers which pull the tape through the apparatus consists of a synchronous motor and a set of reduction gears. The gears have 22 speeds available, ranging from 29 revolutions per minute to 2.17 revolutions per day.* A spring belt drive from the motor shaft is used to operate the take-up reel.

For the detector, a scintillation counter with a silver-activated zinc-sulfide-phosphor and an RCA 5819 photomultiplier tube is ordinarily used.

Although both alpha and beta activities are present in the radioactive substances on the tape, the dynode potentials are usually set so that the counter responds to the alpha activity only. The low background of the alpha scintillation detector, less than one count per two-minute interval, constitutes a distinct advantage over the end-window beta counter for normal monitoring.

The scintillation detector is used in connection with a conventional count-rate meter having integrating-circuit time constants of either 2.8 or 28 sec. A 0.1-ma pen recorder is used to give

* The unit is manufactured by Garrell and Garrell, Haworth, N. J.

a continuous trace of the activity. Zero-drift and calibration checks are made at regular intervals during the operation of the rate meter and recorder.

Operating Conditions

The choice of the proper tape speed, and other operating conditions, can best be determined by a brief consideration of the decay characteristics of the natural radioactivity in the atmosphere. The pertinent members of the uranium and thorium series are given in Table 1.

In the case of radon, experimental decay curves follow very closely those predicted on the assumption that on particulate matter in the air, the daughter products of radon are present in equilibrium amounts. The composite decay curve for the members of this group has, after the first fifteen minutes, an effective half-life of about 40 min. This activity becomes negligible after about 4 hr.

The part played by the thorium series is quite different. Owing to the relatively short half-life of thoron, a smaller fraction of the original amount formed in the earth's crust has an opportunity to reach the surface. Normally, the thoron activity in the atmosphere is only about 5% of the radon activity. Furthermore, the decay of the thoron products is controlled by the 10.6-hr ThB activity. Hence, by using collection times short compared with the ThB half-life, the contribution of the thoron to the activity of a collected sample can be made negligible. Because of the shorter collection times required, and the much higher level of activity, the monitor is normally adjusted to respond to the activity of the radon products.

A 30-min collection time—the time that a given point on the metallic tape is within the precipitator chamber—represents a convenient compromise between maximum saturation of the activity due to the radon products, and the decay of this activity as it passes to the detector. Since the effective collection aperture in the precipitator has a linear dimension of about 2 in., a tape speed of 4 in./hr is required to give the desired 30-min collection time. The time for a point on the tape that is just leaving the precipitator chamber to reach the region directly under the detector is 22 min, a time sufficiently short to prevent serious loss of activity by decay.

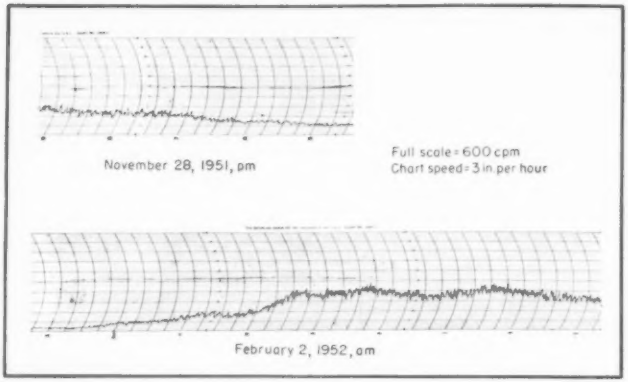

FIG. 3. Recorder tracings showing diurnal variation (November 28, 1951) and effect of strong surface winds (February 2, 1952)

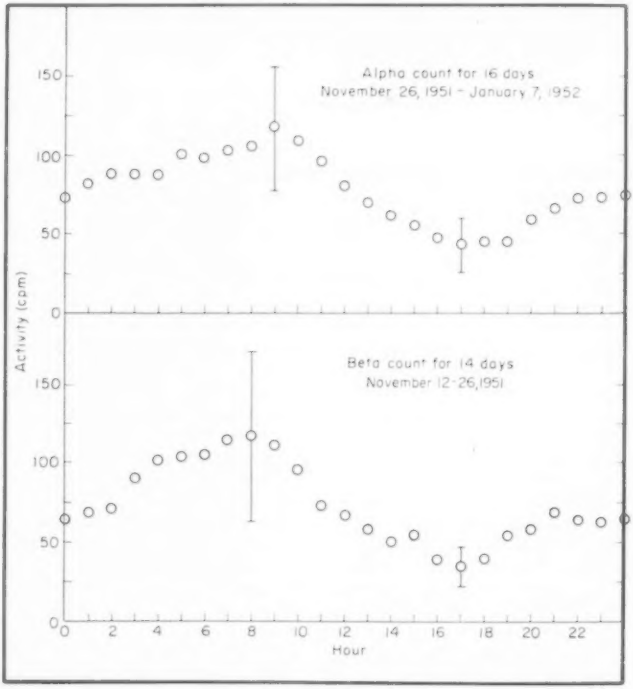

FIG. 4. Average hourly atmospheric activity levels showing diurnal variation

If it is desired to study the activity of the thoron products, the tape speed is reduced to ½ in./hr, and the detector is moved 1½ in. to the right. This gives about a 4-hr delay in counting, the time required for the activity of the radon products to become negligible.

The alpha scintillation counter can be replaced by an end-window Geiger-Müller counter, if it is desired to study

the beta activity in the air. A desirable feature of a monitor of the type described is that it is adaptable to a wide range of purposes.

Results

At present the monitor is being used at the New Mexico Institute of Mining and Technology to furnish data useful in studying the aerosol content of the atmosphere. It is interesting to note that activities ranging from 12 to slightly over 400 cpm have been observed. Variations of as much as a factor of 10 may occur within a single 24-hr period.

Figure 3 shows some typical alpha-activity records. The chart taken from the record of November 28, 1951, illustrates a portion of the diurnal variation in the natural radioactive content of the atmosphere near the ground. In the record shown, the activity reached a minimum of about 60 cpm shortly before 5:00 pm. A gradual increase during the early evening hours was observed, with a level of nearly 180 cpm being reached by 9:00 pm. This level was maintained for several hours, after which the activity again increased, with the maximum occurring in the early morning hours.

The record of February 2, 1952, shown in Fig. 3, illustrates the effect of strong surface winds on the level of activity. At 5:00 am the U. S. Weather Bureau Six-Hourly Synoptic Observation Station, located some 50 meters from the monitor, reported clear skies and zero wind velocity. The monitor showed a normal behavior for such instances, i.e., a relatively high counting rate gradually increasing to a peak activity at about 8:30 am. Beginning at 9:00 am the record taken on a microbarograph operated near the monitor indicated a sharp drop of 0.66 cm of mercury in 4 hr. At 11:00 am the official wind velocity was 14 mph. In the early afternoon, dust laden gusts up to an estimated 50 mph occurred. The chart shows a drop in activity beginning at 9:30 am which can be attributed quite clearly to the comparatively sudden turbulent mixing of air in layers near the surface. Similar, though less striking, examples of this phenomenon have been observed on several occasions.

That the behavior of the curve for November 28 is typical of the diurnal variation is illustrated by the curves of Fig. 4, which show the average hourly alpha and beta activities for the periods indicated. Each of the curves shows minima at about 5:00 pm with build-ups during the night hours. Peaks occur in the neighborhood of 8:00 am. These are followed by a decrease in activity during the daylight hours. The differences between the alpha and beta curves are not considered significant in so far as the diurnal variation is concerned. The probable-error limits shown in Fig. 4 are calculated from the day-to-day fluctuation in activity for the hours of minimum and maximum values. They emphasize the large spread that is encountered in the activity level from one day to the next.

Although a detailed explanation of the diurnal variation curves is not yet available, it appears that the peak can be attributed to the trapping of radon gases in quiescent layers of air near the earth's surface during the night and early morning hours. Vertical transport of the radon gas and product-bearing particulate matter increases as the cold air near the earth's surface is warmed during the day. This results in an observed corresponding decline in activity. With the exception of the time of occurrence of the maximum and minimum activity levels, the main features of the diurnal effects observed herein are consistent with similar variations in the radon (*4*) and RaA (*5*) content of the atmosphere found by other investigators.

Further work involving the use of the monitor is being done in the study of particulate matter of very small sizes suspended in the air, and in the study of the effects of various meterological phenomena on the natural radioactivity in the atmosphere.

* * *

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Irradiated Flies

WITH THE AID of a radiocobalt source, a genetic trick will be pulled on the screw-worm fly, a pest which costs livestock growers millions of dollars annually. Dreamed up by R. C. Bushland, entomologist in charge of the U. S. Department of Agriculture field laboratory, Kerrville, Texas, the trick is based on the fact that the female screw-worm fly is monogamous.

Mr. Bushland plans to sterilize large numbers of laboratory-raised male screw-worm flies by the use of the gamma rays from a radiocobalt source. These sterilized males will be turned loose in heavily infested areas. Since the females mate only a single time, the chances of their mating with a sterilized male are proportional to the number of sterilized males in the population. Furthermore, the eggs from such a union are always infertile. Thus, if enough males can be sterilized and turned loose, a depressing effect on the screw-worm fly population can be achieved.

Preliminary work on the project was started in cooperation with Brooke Army Hospital, Fort Sam Houston, Texas, where the flies were sterilized with X-rays. This procedure was expensive, however, and the problem was taken to the Biology Division of Oak Ridge National Laboratory. There, Dr. C. W. Sheppard helped set up the plan for irradiation with radiocobalt.

Radiophosphorus labeling will also be used in the screw-worm research. The radiophosphorus is added to the hamburger on which the flies are raised and later detected in flies which have been turned loose and then recaptured. Knowing the number of radioactive flies turned loose, and the proportion of captured flies that are radioactive, the total fly population of an area can be calculated.

TABLE 1—Comparison of a Scintillation Solution with Some Commonly Used Organic Crystals

Scintillators	*Emission spectrum, (Å)*	*Electron volts per photon (19)*	*Energy yield*	*Decay time of fluorescence (mμsec)*
Terphenyl in toluene, 8 gm/l	3,400–3,700	150	0.023	2.2 ± 0.3 (*16*)
Naphthalene	3,300–3,600	350	0.010	60 (*17*)
Stilbene	3,980–4,180	105	0.028	6 ± 1 (*18*)
Anthracene	4,250–4,600	65	0.042	23 ± 5 (*18*)

Large-Area Liquid Scintillation Counters

Besides the properties of the scintillator and the photomultiplier used, one must also consider the application in designing liquid scintillation counters. In the building of two types of counters at Princeton, information has been accumulated that can be used as a guide in future design problems

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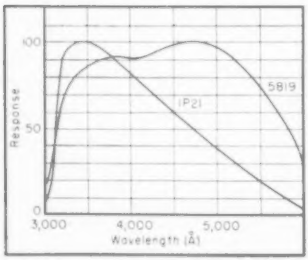

FIG. 1. Spectral sensitivity of type 1P21 and 5819 photomultipliers, showing response to equal numbers of photons at different wavelengths

USEFULNESS of the scintillation counter has been limited in some cases because the crystals available were at most a few inches in size. In the study of cosmic rays, for instance, counter areas of the order of square feet are often necessary to get reasonable counting rates. Now, the development of the liquid scintillation counter has made it easy to build scintillators of any size or shape, and the useful size is limited only by the difficulty of collecting a large enough fraction of the light emitted in a scintillation.

Properties of Liquid Scintillators

A survey of the properties of scintillation crystals has been given by Hofstadter (*1*). Table 1 compares the properties of some of the commonly used organic crystals with those of a saturated solution of terphenyl in toluene, which is representative of the most efficient liquid scintillators known.

The figures given for energy yield are based on a measurement with a photomultiplier calibrated by the Radio Corporation of America, and are thought to be accurate to within a factor 1.5. They are in approximate agreement with the figures of Hopkins (*2*), who bombarded an anthracene crystal with monoenergetic electrons, collecting one photoelectron from the cathode for every 1.4–2 kev of electron energy. Assuming 100% light collection and a 5% cathode efficiency of the

* PRESENT ADDRESS: Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

TABLE 2—Comparison of Solutions for Large Scintillation Counters

Solution	*Concentration (gm/l)*	*Relative light yield*	**Emission (Å)*
Terphenyl in toluene	8	100	3,400–3,700
Terphenyl in *p*-xylene	8	100	3,400–3,700
Terphenyl in *m*-xylene	8	100	3,400–3,700
Terphenyl in *o*-xylene	8	100	3,400–3,700
Terphenyl in benzene	8	83	3,400–3,700
α-naphthylamine in xylene*	2	41	3,900–5,600
β-naphthylamine in xylene*	4	20	3,900–5,600
Pyrene in xylene	10	28	3,700–4,000
Fluroanthene in xylene	5	30	blue

* Solution turns yellow on standing

TABLE 3—Absorption Length in Various Solvents for the Light Emitted in a Scintillation in Terphenyl Solutions*

Liquid	*Absorption length (cm)*
Toluene	40.9
o-xylene	27.4
m-xylene	18.5
p-xylene	11.4

* Measurements on unpurified solvents by A. Meyer, Princeton University. More recent measurements on purified solvents to be reported (*20*).

photomultiplier, this gives 70–100 electron volts per photon. The values are also compatible with Hofstadter's (*3*) figure of 1 kev per photoelectron in NaI. The figure for energy yield is the energy of a photon at the mean wavelength of the scintillations divided by the number of electron volts per photon—it represents that fraction of the energy lost by an ionizing particle which is converted into useful light in the scintillator.

The characteristics of the more common liquid scintillators are listed in Table 2. Many other solutions have been tried in this laboratory during the past two years, but those listed serve to illustrate the points necessary for the consideration of large tanks. As has been pointed out (*4, 5*), the dependence of the light output of a solution on concentration shows a saturation. The concentration listed is that at which the light output is at the maximum value. No correction has been made for the spectral response of the 5819 photomultiplier.

Except for the decay times of the fluorescence, the figures in Tables 1 and 2 are based on measurements made at Princeton. Our values have proved reproducible to 5%, and the differences between the results with terphenyl in *o*-, *p*- and *m*-xylene and toluene have been no greater than this.

These results do not always agree with those obtained elsewhere. The discrepancies are assumed to be due to small amounts of impurity in the solvent—Kallmann (*5*) has shown that some impurities quench the fluorescence appreciably when they are present at a concentration of a few parts in a million. Since the solvents certainly have impurities to a greater extent than this, their properties in a liquid scintillator depend on whether any quenching material is present, rather than on the over-all purity.

All of our solvents were bought from the Matheson Co., Inc., East Rutherford, N. J. In one experiment, a solution of terphenyl in "pure" *p*-xylene obtained from another source was found to give a light output only 73% as great as the same terphenyl in Matheson *p*-xylene. This is mentioned merely to point out the variation that may be expected from the presence or absence of unknown impurities.

An impurity in the solute is not expected to be important, if the material is known to make satisfactory scintillation crystals, since any impurity is diluted by a factor of at least 100.

The absorption in the organic solvents of the light emitted in terphenyl fluorescence is shown in Table 3. A comparison with Tables 2 and 3 shows that, for the large-area liquid scintillators, a solution of terphenyl in toluene appears to be the best scintillator listed, since it has the greatest light output and the smallest light absorption. It should again be emphasized that these results refer to one particular batch of chemicals, and can be affected by impurities at very low concentrations.

TABLE 4—Photomultiplier Characteristics

Photomultiplier	5819	1P21
Cathode area	11.6 cm²	1.9 cm²
Maximum quantum efficiency	6.5%	13%
Wavelength of maximum	4,800 Å	3,500 Å

Properties of Photomultipliers

The RCA photomultiplier tubes most suitable for use in scintillation counters are the 1P21 and the 5819—and perhaps also the C-7151, which is similar to the 5819 except for its smaller size. Absorption in the glass envelopes of these tubes is small for light of wavelengths greater than 3,400 Å, so that the special glass of the 1P28 and C-7140 offers little advantage for use with the scintillators considered here.

Typical spectral response curves for the two types are shown in Fig. 1. 1P21 tubes are uniform in spectral response, but curves for the end-window tubes vary in the position and relative height of the two peaks shown at 3,700 and 4,800 Å. Both tubes are well matched to the organic scintillators discussed here. The effects of the different cathode geometries are discussed in a later section.

Table 4 gives a comparison of the characteristics of type 1P21 and 5819 tubes, based on the figures given by RCA. These figures are averages, and we shall use them in our comparison of the two types, although it must be remembered that individual photomultipliers show considerable variations from the norm.

Detection of Radiation

One property common to all organic scintillators, solid and liquid, is nonlinearity of energy response. Experi-

mentally, it is found that the variation of light output along the path is given as a function of ionization density by the formula (6, 7)

$$\frac{dS}{dr} = \frac{A\dfrac{dE}{dr}}{1 + B\dfrac{dE}{dr}}$$

where dS/dr is the light output in the path element dr, and dE/dr is the rate of energy loss. For anthracene and stilbene, the constant B has the value 8.8×10^{-3} gm cm^{-2} Mev^{-1}. Measurements with alpha particles in terphenyl solutions, at a concentration of 5 gm/liter, give approximately the same value for B. The value of B increases—that is, the deviation from linearity becomes greater—as the concentration of terphenyl decreases. Figure 2 shows the variation of light output with energy for protons and electrons which stop in an anthracene crystal. We shall assume that the same curve holds for terphenyl solutions of about 5 gm/l concentration. The deviation from linearity is negligible for electrons of more than 80 kev.

An organic scintillation counter is an efficient detector of fast neutrons. The scintillations are due to recoil protons resulting from the elastic scattering of neutrons by the hydrogen nuclei in the solvent. The mean free path for this process is shown in Fig. 3 (8). The distribution in energy of the recoil protons is flat, with all values between 0 and E_n, the energy of the incident neutron, being equally likely.

In organic scintillators, gamma rays in the energy range 25 kev–25 Mev are detected principally by the Compton effect. The mean free path of gamma rays in the solution is shown in Fig. 4. The mean energy of the recoil electron, and hence the mean pulse height, is shown as a function of gamma-ray energy in Fig. 2.

Construction of Tanks

Scintillation tanks have been constructed at Princeton for use in a cosmic-ray experiment (9). The design of these tanks could certainly be improved, since our primary aim has been to get a counter that worked, rather than delay the experiment in an attempt to optimize the detector. Two types are in use, both having metal containers, one using 1P21's and the other 5819's. Plan views are shown in Fig. 5.

The 1P21 tank, designed to cover a large area, has a sensitive volume of about $1 \times 12 \times 12$ in. The windows are of $\frac{1}{8}$-in. Pyrex, and were found to absorb not more than about 2% of the light from the solution. The gaskets were made from lead wire. The fact that the liquid is in contact only with glass and metal, and that 1P21 tubes are used, gives this counter a long life; one counter of this type has been in use continuously for a year and shows no sign of deterioration.

This tank was designed to detect the passage of ionizing particles through the solution. Its over-all efficiency for the detection of particles of minimum ionization was found to be 70% with the discriminator level set so as to accept 400 noise counts per second. The over-all height of the tank, including the photomultiplier housing and preamplifier, is 2 in. The detection efficiency could be improved without much change in the outside dimensions by increasing the solution depth to 2 in.

The 5819 tank has a sensitive volume of $3 \times 3 \times 12$ in. The liquid is directly in contact with the photomultiplier envelope, and the seal is made with a Neoprene O-ring gasket.* These gaskets must be soaked in several changes of toluene or xylene to remove impurities which would otherwise discolor the solution. During the soaking they stretch, and usually fit loosely over the tube after removal from the bath. They shrink rapidly, however, and if left around the tube will grasp it tightly. In spite of the fact that they are originally too small to fit over the photomultiplier, we have never had a tube crushed. The Neoprene does not appear to poison the solution to any great extent.

The seals are shown in Fig. 6. They are made of iron to afford the tube some protection from the earth's magnetic field. If the counter is to be used in a stronger magnetic field, a more elaborate shield will be necessary. In the assembly of the seal, a certain amount of courage is necessary; but we have always found it possible to stop the leakage, by sufficient tightening, without breaking the tube. After the tank has been put into operation, the toluene or xylene of the solution makes the gasket swell sufficiently to stop any small leaks that may have been overlooked.

In a tank of this type the photomultiplier cathodes should be run at ground potential; otherwise the cathodes deteriorate in the course of a few month's operation, presumably because of the voltage gradients in the glass.

This tank was designed to detect the neutrons and gamma rays resulting from μ-meson capture. Its detection

* Neoprene O-ring gaskets No. 1820-30, made by Linear, Inc., State Road and Levick St., Philadelphia 35, Pa. We are indebted to L. Zernow for information on these gaskets.

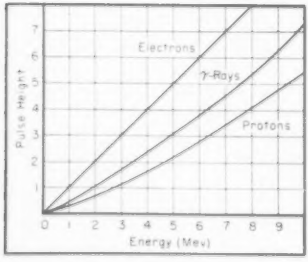

FIG. 2. Variation of light output with energy in a 5 gm/liter terphenyl solution

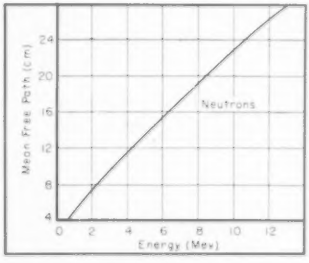

FIG. 3. Mean free path of neutrons in a liquid scintillator, as a function of energy

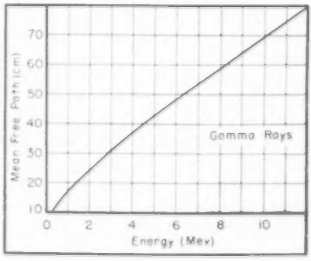

FIG. 4. Mean free path of γ-rays in a liquid scintillator, as a function of energy

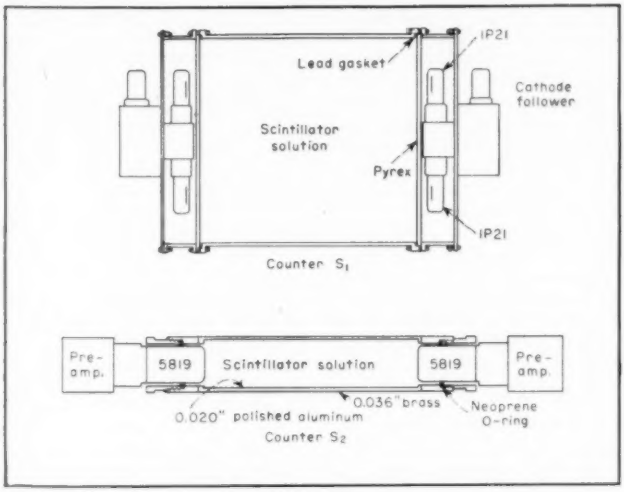

FIG. 5. Two scintillation tanks

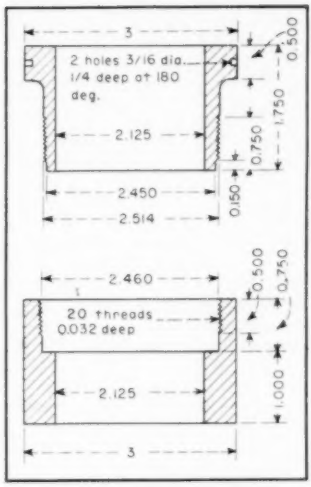

FIG. 6. Seal for tank using type-5819 photomultipliers

efficiency has not been measured directly, but can be estimated to be of the order of 10–20% for the detection of each.

Both of the tanks were lined with polished sheet aluminum. Magnesium oxide was not used because it was feared that it might be washed off the walls and become suspended in the solution, making it cloudy; in addition, the effect of the refraction coefficient of the liquid on the reflectivity of the coating was not known. When the reflector is not in contact with the solution, there seems to be no *a priori* reason to choose specular rather than diffuse reflection. Magnesium oxide has been found, in some cases at least, to give the best results (*10*).

A third type of tank, which has not been tried at Princeton but was described by Ney (*11*), is a Pyrex or quartz cell, with the photomultiplier outside. If an end-window tube is used, it should be placed in optical contact with the scintillator. A reflector of magnesium oxide or aluminum should be placed loosely around the outside, so as to allow for internal reflection.

Problems of Light Collection

The design of a large-area scintillation counter depends upon whether one wishes to measure the light output in a scintillation quantitatively, or merely to detect the passage of a particle.

In the first case, it is necessary that the light collection be uniform over the volume of the liquid, and that enough light be collected from each event so that statistical fluctuations in pulse height are sufficiently small. The standard deviation in pulse height, in a scintillation in which a given number of photons are released at a given position relative to the cathode, is (*12*)

$$\frac{\delta V}{V} = \sqrt{\frac{\sigma}{n(\sigma - 1)}}$$

where V is the pulse height, n the number of photoelectrons collected into the first dynode, and σ the gain per stage of the photomultiplier. If we wish to determine the amount of light emitted to within 25%, and take $\sigma = 4$, corresponding to about 100 volts per stage, we find that it is necessary to collect 21 photoelectrons. At this level there is no trouble in discriminating against noise, so that the design limitations are determined by the allowable error in pulse size.

The tanks described in the preceding section were not designed for pulse-height measurements, and we have therefore not determined the uniformity of light collection over their volumes.

If one needs only to detect the passage of a particle through the scintillator, and if in addition one can tolerate a certain background noise rate and a certain inefficiency, the amount of light collected may be much smaller, and the light collection need not be uniform from various parts of the tank. To take a concrete example, let us consider the 1P21 tank described in the preceding section, and set the allowable total noise rate at 400 counts per second. Then from the pulse-height distribution of noise pulses shown in Fig. 7, we find that the discriminator must be set at a level equal to 1.8 times the size of the average pulse from one photoelectron, which we call an equivalent electron, after Morton (*12*). If, on the average, m photoelectrons are collected, the detection efficiency can be calculated from the integral pulse-height distribution due to m electrons, and the bias setting selected on the basis of noise. The pulse-height distribution for m electrons can be obtained from that of a single electron incident on the first dynode. Figure 8 shows this distribution, calculated for a gain of 4 per stage, on the assumption that the multiplication in each dynode follows a statistical law with a Poisson distribution. The shape of this curve has been verified experimentally.

The depth of the liquid in the tank is about 1.8 gm/cm², so that a particle at minimum ionization will lose 2.7

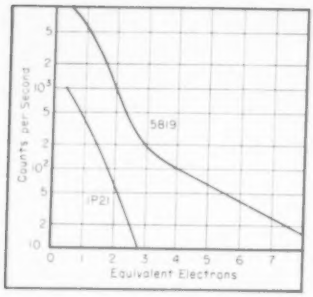

FIG. 7. Integral pulse-height distributions of noise pulses in representative photomultipliers

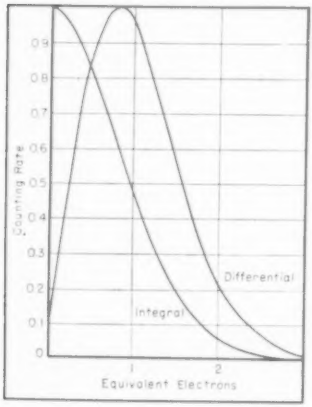

FIG. 8. Differential and integral pulse-height distribution for single photoelectrons. One equivalent electron is the average height of these pulses

Mev of energy in the scintillator. If we count on one photon for every 200 ev of this energy—since the concentration is lower than that listed in Table 1—we find that 13,500 photons are generated in each scintillation of the kind considered. The total solid angle subtended by the photomultiplier cathodes at the center of the tank is 0.0019, and we may expect that the variation of solid angle will not be very great, at least over the central portion of the tank. If we take 0.0019 as a mean solid angle, we expect 23 photons to arrive at the cathodes. Allowing for a 15% loss by reflection at the three glass-air interfaces, and for light absorption in the toluene, we must reduce the number arriving to 11. We estimate that we gain a factor of 3 or 3.5 by reflection in the aluminum; our final figure for the number of photons collected is therefore 30–40. On the average we shall expect 3 or 4 photoelectrons, and a counting efficiency of 70–85% for particles of minimum ionization. This agrees with the measured efficiency rather better than might be expected in view of the variation of noise rates between different tubes, and of our neglect of the effects of light absorption by the terphenyl. We may hope that the reduction in light output because of the latter effect will be small, because of the high probability that any photon which is absorbed by a terphenyl molecule will be re-emitted (*13*).

Choice of Photomultiplier

As pointed out previously, the photomultipliers most suitable for use with the scintillators discussed here are the types 1P21 and 5819. The choice between these two tubes is governed by considerations of the amount of space available, and of whether or not pulse-height measurements are desired. The average quantum efficiency of the 5819 cathode is only 40% as great as that of the 1P21 cathode for light of 3,500 Å. But its area is six times as great, so that under the same geometrical conditions one would expect to get 2.4 times as many photoelectrons from a given scintillation. In addition, the 5819 has the advantage that its cathode may be put in optical contact with the scintillator, thus increasing the light collection both because of the larger solid angle and because there is no chance of light reflection at the surface of the scintillator or of the glass envelope of the tube. The difference in light collection due to this depends on the geometry and is difficult to calculate exactly. In a 1-ft² tank, the loss of light entering a 1P21 might be about 15% due to reflection at three glass-air interfaces, and another 25 or 30% because its photocathode is farther from the scintillation than that of the end-window tube would be; in this respect, the 5819 would have an advantage of a factor of about 1.5. This raises to 3.6 the ratio of the number of photoelectrons from a given scintillation, which is the figure of merit in applications where the pulse height is to be measured. In addition, it is easier to make light collection uniform in a tank with 5819's than in one with 1P21's.

In applications not concerned with pulse-height measurements, the limiting factor will be noise, and we must take into account the difference in discriminator setting for the two types of tubes. Let us repeat the calculations of the last section, this time for the tank with two 5819's, again limiting the total noise rate to 400 cps.

Figure 7 gives the noise pulse-height distribution in a representative 5819. The shapes of these curves vary widely for different photomultipliers of this type, especially in the exponential tail. From the figure, the discriminator setting for a noise rate of 200 cps per tube is 3 equivalent electrons. On the basis of the noise rates shown, we find that we must collect on the average 1.7 times as many photoelectrons from a scintillation in the 5819 tank as in the 1P21 tank, for the same detection efficiency. Thus the advantage of the 5819 tank relative to the one with 1P21's is $3.6/(2 \times 1.7) \sim 1.0$. In other words, in this application one 5819 is about equivalent to two 1P21's.

Satellite Pulses

It has been found experimentally (*14*) that a single pulse in a photomultiplier is often followed by one or more secondary pulses, comparable in size to noise pulses. These satellite pulses occur both in 1P21's and 5819's. They are distributed in time, with a mean lag after the main pulse of approximately 0.3 μsec in the 1P21 and 1 μsec in the 5819. They are thought to be due to single positive ions, produced by the electrons of the main pulse drifting back and striking an electrode.

Satellite pulses present a serious problem in the design of an experiment using scintillation counters, unless the arrangement is such that only the first pulse from each scintillation is counted, or that the light collection is sufficiently good so that the satellites may be discriminated against on the basis of pulse height.

Conclusions

The important characteristics of the liquid scintillation counter are: (1) large counter volumes, (2) fast response, making possible timing measurements in the millimicrosecond region, (3) high sensitivity to gamma rays and fast neutrons, and (4) a dependence of light output upon rate of ionization loss. The nonlinearity

of energy response and the geometrical conditions imposed by the need of limiting statistical fluctuations in pulse height, limit the usefulness of large liquid scintillation counters as high-density ionization chambers.

Large liquid scintillators will probably be used most extensively in the detection of fast neutrons. Jordan (*15*) has listed the following properties as being desirable in a fast neutron counter: high efficiency, prompt response to the passage of a fast neutron, and gamma insensitivity. Organic scintillation counters are the only ones which combine the first two properties; their drawback lies in their sensitivity to gamma rays, which are often present in neutron beams. It is also unfortunate that they cannot be used directly to determine neutron energies, because of the distribution in energy of the recoil protons; however, if the neutron beam were collimated, neutron energies might be measured by an arrangement similar to Hofstadter's two-crystal γ-ray spectrometer (*3*).

The large-area counters described here are also useful in cosmic-ray measurements whenever fast timing is required, especially when neutrons or gamma rays are to be counted. They have proved to be well suited to the μ-meson capture experiment mentioned previously (*9*), in which they are used to determine the time interval between the arrival of a meson and the emission of a neutron or gamma ray resulting from nuclear capture of the meson. The over-all timing uncertainty in this experiment was found to be about 2 mμsec.

* * *

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Predicting Long-Distance Damage by A-Bombs

BLAST DAMAGE from atomic bombs at great distances is more dependent on the weather (temperature and wind) than on the bomb's size. Near the explosion, the blast wave rolls out along the ground, but farther than 5 or 10 miles from the explosion, the blast effect becomes an acoustical problem.

E. F. Cox, of Sandia Laboratory, Albuquerque, N. M., recently described the tests on distant blast effects carried out at the Nevada Test Site last September. The results of the program show why windows were broken in Las Vegas, 80 miles from the test site, and why the atomic explosions were felt even farther away.

In an ideal atmosphere, there would be no winds and temperature would decrease with altitude. Since sound travels slower in cool air than in warm air, all blast waves from an explosion would bend upward and none would return to earth. However, with temperature inversion, a common meteorological phenomenon, sound speed increases with altitude. The sound wave from the blast is thus bent downward, focusing at some point on the ground, is reflected up, and then repeats its path. Since the focusing effect is not sharp, this effectively creates bands of silence and noise fanning out from the explosion. The greatest energy is transferred, however, at the focal point.

In one test, air temperature decreased from 0 to 6,000 ft, then increased (inversion) from 6,000 to 12,000 ft. This resulted in a band of silence out to 21 miles, then a zone of noise from 21 to 30 miles. On striking the earth, the sound waves were reflected, resulting in another noise band from 42 to 60 miles, and so on.

Actually the energy transferred by this effect are small—less than that in a 35-mph wind. However, the blast energy, which is a positive pressure, is followed by a period of negative pressure. Thus, the windows broken in Las Vegas, at the approximate focal point of one test atomic explosion, were not pushed in, but were pulled out by the vacuum created by the negative pressure. These were plate-glass windows in stores, solidly braced against external, positive pressures, but held in place on the outside by only thin metal strips.

Can the focal point of a blast be predicted? Theoretically, yes, but there are two problems in attempting to predict where blast damage will occur and how severe it will be. One of these is the changeability of the weather. Very small changes in temperature or wind can cause quite large changes in blast focal points.

The other problem is caused by the fact that the ozonosphere, an atmospheric layer that extends from 25 to 40 miles above the earth, bends many of the sound waves that normally would not strike the earth's surface again, returning them once more. Unfortunately, present-day meteorological instruments cannot be used to obtain routine data on weather effects in this region.

The effects of "reflection" by the ozonosphere cause a noise band from about 120 to 170 miles. Once again, the focal point lies on the near side of the band.

The problem of predicting distant blast effects is not a new one. Some measurements were made in Germany at the end of the last war, when the demolition of ammunition dumps was coordinated with meteorological measurements. However, the data obtained does not appear to be statistically reliable.

Ventilation Requirements for Power Reactor Compartments

The problem of personnel protection is not limited to direct radiation—contamination of air by coolant that leaks from the reactor heat transfer system must be considered

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THE PREVENTION of excessive exposure of personnel to radioactivity accompanying the production of energy by nuclear fission may be broken down into two parts: (1) Personnel must be shielded from the direct radiation of the reactor core. (2) Air contamination by leakage of the radioactive coolant must be kept below the maximum permissible level.

This paper deals with ventilation requirements for power reactor compartments, as determined from Barnes' estimated breathing tolerances (*1*). Although calculations are based on water as the coolant, the method is applicable to other coolant systems.

Essentially, the system for which this analysis is made consists of a thermal nuclear reactor, a heat exchanger, a pump, and the associated piping, all housed in a compartment as shown in Fig. 1. The coolant absorbs heat in the reactor, is pumped to the heat exchanger where it liberates its energy in the production of steam, and then returns to the reactor to start a new cycle.

In the reactor, many of the neutrons diffusing through the core are captured by nuclei of the reactor coolant and the nuclei of the impurities in the coolant, and effect the production of radioisotopes. By far, the greatest part of the radioactivity is induced by the thermal flux.

All the calculations to follow are based on the following assumptions:

1. Only the production of radioisotopes by the capture of thermal neutrons need be considered as being of significance.

2. Personnel in the reactor compartment are not subjected to direct radiation from the reactor system.

3. All components in the system in contact with the coolant are either made of or clad in type-347 stainless steel.

4. The coolant in the system is water. The system pressure must be equal to or greater than saturation pressure for the highest temperature in the system.

Corrosion Products

The corrosion products to be found in the reactor coolant were determined from the corrosion of type-347 stainless steel by water in a dynamic loop. The tests (*2*) were carried on for a period of 30 days at 500° F and with a water velocity of 20 ft/sec.

Need for Ventilation

In air-cooled reactors, the constant withdrawal of air creates a negative pressure inside the shielding, so that little if any radioactivity is released to the air in the reactor compartment. In liquid-cooled reactors too, exhaust blowers are used to ventilate the reactor interior (NU, Nov. '51, p. 10), but the circulation of coolant in a closed system carries radioactivity outside of this protected area. A leak in the coolant system can cause contamination of the air in the compartment. Compartment ventilation systems have been briefly described before (NU, Dec. '50, p. 12), but this is the first complete treatment of ventilation requirements.

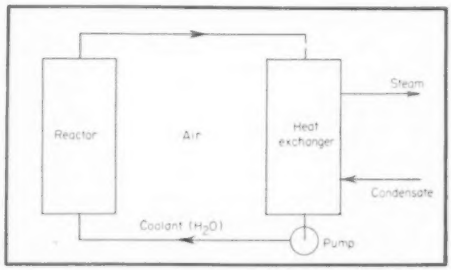

FIG. 1. Reactor compartment

Impurity Abundances, Radioactivities, and Biological Data

Nuclear reaction	Parent in coolant (ppm)	No. atoms parent per cm³ coolant (sp. gr. 1)	Radioactivity of daughter [(1/ϕRG) c/cm³ coolant] 30 hr	120 hr	480 hr	∞ hr	Breathing tolerances ($\mu c/m^3$ air) Exposure 1 hr/wk	Continuous exposure
$Fe^{58}(n,\gamma)Fe^{59}$	0.00231	0.249×10^{16}	0.0746×10^{-22}	0.289×10^{-22}	1.035×10^{-22}	3.97×10^{-22}	0.1	0.001
$Fe^{54}(n,\gamma)Fe^{55}$	0.0405	4.37×10^{16}	0.147×10^{-22}	0.587×10^{-22}	2.34×10^{-22}	2.48×10^{-20}	30	0.2
$Cr^{50}(n,\gamma)Cr^{51}$	0.0297	0.334×10^{16}	0.0481×10^{-19}	0.179×10^{-19}	0.596×10^{-19}	1.46×10^{-19}	2	0.02
$Ni^{58}(n,\gamma)Ni^{59}$	0.524	5.29×10^{16}	0.0715×10^{-25}	0.286×10^{-25}	1.142×10^{-25}	0.6×10^{-18}	20	0.2
$Ni^{64}(n,\gamma)Ni^{65}$	0.0069	6.97×10^{13}	0.49×10^{-20}	0.49×10^{-20}	0.49×10^{-20}	0.49×10^{-20}	100	1
$Mo^{92}(n,\gamma)Mo^{93}$	0.1053	0.662×10^{16}	0.171×10^{-22}	0.179×10^{-22}	0.179×10^{-22}	0.179×10^{-22}	40	0.4
$Mo^{98}(n,\gamma)Mo^{99}$	0.158	0.99×10^{16}	0.393×10^{-20}	1.05×10^{-20}	1.46×10^{-20}	1.47×10^{-20}	5	0.3
$Mo^{100}(n,\gamma)Mo^{101}$	0.064	0.402×10^{16}	0.816×10^{-20}	0.816×10^{-20}	0.816×10^{-20}	0.816×10^{-20}	800	7
$H^2(n,\gamma)H^3$		1.042×10^{19}	0.0348×10^{-21}	0.139×10^{-21}	0.557×10^{-21}	1.83×10^{-19}	3,000	30
$Na^{23}(n,\gamma)Na^{24}$	0.394	1.039×10^{16}	0.1165×10^{-18}	0.150×10^{-18}	0.154×10^{-18}	0.154×10^{-18}	200	2
$C^{13}(n,\gamma)C^{14}$		2.68×10^{17}	0.0301×10^{-23}	0.1205×10^{-23}	0.483×10^{-23}	0.724×10^{-18}	10	0.1
$O^{17}(n,\alpha)C^{14}$		0.1303×10^{20}	0.0703×10^{-21}	0.281×10^{-21}	1.125×10^{-21}	0.169×10^{-18}		
$O^{18}(n,\gamma)O^{19}$		0.681×10^{20}	0.405×10^{-18}	0.405×10^{-18}	0.405×10^{-18}	0.405×10^{-18}	150	0.9
$Cl^{37}(n,\gamma)Cl^{38}$	0.149	0.262×10^{16}	0.354×10^{-19}	0.354×10^{-19}	0.354×10^{-19}	0.354×10^{-19}	200	1
$Ca^{44}(n,\gamma)Ca^{45}$	0.0147	2.21×10^{14}	0.0187×10^{-21}	0.0752×10^{-21}	0.29×10^{-21}	0.358×10^{-20}	0.3	0.003
$Ca^{46}(n,\gamma)Ca^{47}$	2.36×10^{-5}	3.43×10^{11}					2	0.02
$Ca^{48}(n,\gamma)Ca^{49}$	0.00132	1.98×10^{13}	0.295×10^{-21}	0.295×10^{-21}	0.295×10^{-21}	0.295×10^{-21}	60	0.6
$Mg^{26}(n,\gamma)Mg^{27}$	0.068	1.68×10^{15}	0.227×10^{-20}	0.227×10^{-20}	0.227×10^{-20}	0.227×10^{-20}	1,600	14
$Si^{30}(n,\gamma)Si^{31}$	0.0143	3.08×10^{14}	0.1×10^{-20}	0.1×10^{-20}	0.1×10^{-20}	0.1×10^{-20}	150	1.3
$Mn^{55}(n,\gamma)Mn^{56}$	0.774	8.48×10^{15}	0.296×10^{-17}	0.296×10^{-17}	0.296×10^{-17}	0.296×10^{-17}	70	0.6
$Cb^{93}(n,\gamma)Cb^{94}$	0.70	4.54×10^{15}	1.59×10^{-19}	1.59×10^{-19}	1.59×10^{-19}	1.59×10^{-19}	5,000	50

The following coolant impurity quantities, in parts per million, are the averages of two sets of data: NaCl, 1; Fe_2O_3, 1; Cr_2O_3, 1; NiO, 0.4; MoO_3, 0.05; CaO, 1; MgO, 0.5; SiO_2, 2.0; MnO, 0.1; Cb_2O_5, 0.02; and CO_2 is 10 cm³/l (at standard conditions).

Certain isotopes of these impurities react with thermal neutrons and produce radioisotopes, as listed in the table on this page. Knowing the isotopic distribution of the natural elements (*3*, *4*), the number of parent atoms per cm³ in coolant of unit specific gravity can be calculated.

The parts per million for the elements hydrogen and oxygen are excluded because it is known in what proportions they combine to form water.

Impurity Radioactivities

The relationship giving the radioactivity in disintegrations per sec of any particular radioisotope at time t when being bombarded by neutrons is

$$N\lambda = \phi \Sigma a (1 - e^{-\lambda t}) \qquad (1)$$

where ϕ is the neutron flux in neutrons/cm² sec; λ is the decay constant; t is the time in seconds; N is the number of radioactive atoms per cm³; and Σa, the macroscopic cross section, is the product of σ, the probability of an encounter between a neutron incident upon 1 cm² and a nucleus in that area, and u, the number of atoms in each cubic centimeter.

This equation holds when the material is being irradiated continuously. However, when coolant is being pumped through a circuit and is being irradiated only part of the time, the equation becomes

$$N\lambda = \phi \Sigma a R (1 - e^{-\lambda t}) \qquad (2)$$

where R is the ratio of the time spent in the reactor to the time spent making one complete cycle.

The calculation of all activities is based on ϕ, R, and the specific gravity G, each being equal to unity. In this manner the information is made less specific. Thus, in the table are listed the "unit" daughter radioactivities after various periods of irradiation. All that need be done to obtain the actual value of these radioactivities is to multiply these calculated values by the factor ϕRG, determined by the conditions of the system.

The total radioactivity in the coolant rises very sharply during the first several hours, and then continues to rise at a very slow, but almost constant rate. The initial rapid rise is produced by the short half-lived isotopes Na^{24}, Mn^{56}, O^{19}, and Cb^{94} which have high activities and reach equilibrium rapidly, and the slow

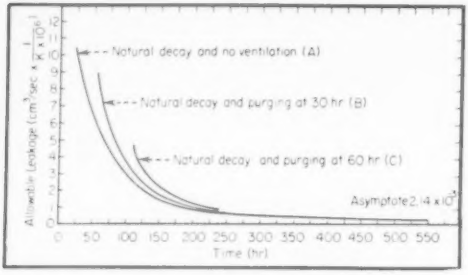
Natural decay and no ventilation (A)
Natural decay and purging at 30 hr (B)
Natural decay and purging at 60 hr (C)
Asymptote 2.14 x 10⁻³
Allowable Leakage (cm³/sec x 1/K x 10⁶)
Time (hr)

FIG. 2. Allowable leakage rates for continuous exposure (no ventilation and periodic ventilation)

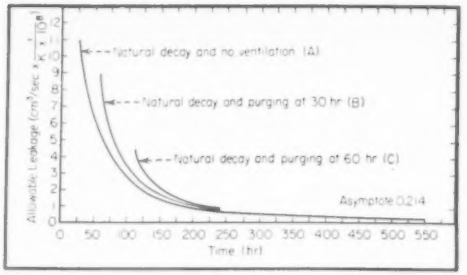
Natural decay and no ventilation (A)
Natural decay and purging at 30 hr (B)
Natural decay and purging at 60 hr (C)
Asymptote 0.214
Allowable Leakage (cm³/sec x 1/K x 10⁶)
Time (hr)

FIG. 3. Allowable leakage rate for 1 hr/wk exposure (no ventilation and periodic ventilation)

increase is due to the presence of the long half-lived elements Fe^{59}, Fe^{55}, Cr^{51}, and Ni^{59} which are still far from equilibrium.

It will be noted that all the reactions considered, except $O^{17}(n,\alpha)C^{14}$, are (n,γ) reactions. Although most (n,α) reactions ordinarily require a certain minimum energy called the threshold energy, this particular reaction can be effected by the capture of a thermal neutron.

No radioactivities are listed for Ca^{47} because data on the cross section for the reaction are not available. It was calculated that if the presence of Ca^{47} were to affect the results, the reaction $Ca^{48}(n,\gamma)Ca^{47}$ would have to have a cross section of approximately 2,000 barns. It is highly improbable that the value would be this high.

Allowable Coolant Leakage

The contamination of compartment air due to leakage of the coolant has been investigated for three conditions: no compartment ventilation, periodic compartment ventilation, and filtering of compartment air or continuous compartment ventilation.

Just as activities are calculated for each of the radioisotopes after various periods of irradiation in the reactor (see table), allowable leakage rates are determined from breathing tolerances for the same periods of time assuming only one radioisotope at a time to be present in the reactor coolant. The allowable leakages thus calculated are then "added" according to the relation

$$1/L = 1/L_1 + 1/L_2 + 1/L_3 + 1/L_4 + \ldots$$

where L is the total allowable leakage, and L_1, L_2, L_3, L_4, . . . are the allowable leakages assuming only one radioisotope present at a time in the coolant.

This is a conservative method because it implies that all radioisotopes affect all parts of the human body equally. It might actually happen that element X deposits itself in the marrow of the bones and would do the greatest damage there, while element Y would deposit itself in the liver. As a result the allowable leakage might have the same value whether elements X, Y, or both were present in the coolant at any time. This is an extreme example, but there is a tendency for this kind of action to take place.

No compartment ventilation. It might be suspected that the allowable leakage of radioactive coolant from the system for conditions with no ventilation would be almost constant after the initial period during which the radioactivity is building up so rapidly. This is not true, however, because the allowable leakage is not merely a function of the total activity, but rather a function of the activities of the various isotopes present in the coolant, and the breathing tolerances for each isotope.

Assuming only one radioisotope present in the reactor coolant, let l be the number of radioactive atoms leaking per sec from the reactor system per cm^3 of compartment air; N', the number of radioactive atoms per m^3 of compartment air; L, the coolant leakage in cm^3/sec; V, the compartment air volume in m^3; G, the specific gravity of coolant; and B, the breathing tolerance for the radioisotope in dps/m^3. Then

$$dN'/dt = l - \lambda N' \qquad (3)$$

Integrating Eq. 3, using $l = LN/V$ and Eq. 2, and introducing the breathing tolerance B, we get

$$L = \frac{\lambda BV}{N\lambda(1 - e^{-\lambda t})} \qquad (4)$$

which may be rewritten as

$$L = \frac{\lambda B}{(1 - e^{-\lambda t})\underline{N\lambda}} \times \frac{V}{\phi RG} \qquad (5)$$

where $\underline{N\lambda}$ is the radioactivity calculated for ϕ, R, and G each being equal to unity.

For those elements which have long half-lives, the allowable leakage is large at first and then tapers off rapidly until near-equilibrium conditions are attained. Isotopes with short half-lives reach equilibrium in the coolant rapidly; and, because $\underline{N\lambda}$ and $(1 - e^{-\lambda t})$ are constant at a very early time, the allowable leakage may be considered as constant.

Curves A in Figs. 2 and 3 follow the conditions for long half-lived elements very closely. The allowable leakage for short periods of operation is almost wholly determined by Cr^{51} and Mn^{56}. The isotope Cr^{51} predominates because of a high-valued cross section for the reaction producing it, and its low breathing tolerance. The Mn^{56} becomes important because of its abundance and the high cross section for the $Mn^{55}(n,\gamma)$ reaction.

Because Cr^{51} has a long half-life, the allowable leakage for periods of operation greater than 120 hr is determined by its presence. But for this isotope, the allowable leakage rates would be approximately ten times the values plotted at 480 hr of operation.

The radioisotopes Fe^{59}, Mo^{99}, and Ca^{45}, are also of some importance in

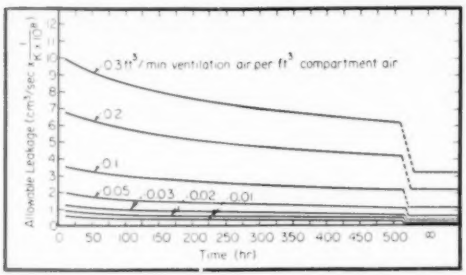

FIG. 4. Compartment ventilation requirements for continuous exposure

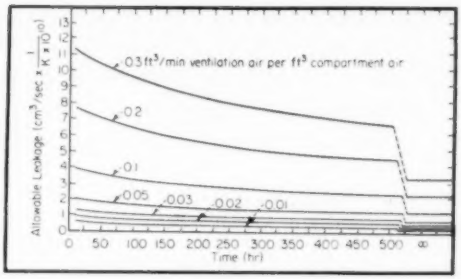

FIG. 5. Compartment ventilation requirements for 1 hr/wk exposure

determining the shapes and the values of the curves in Figs. 2 and 3.

The curves in Figs. 2 and 3 state (for the conditions noted) that a leakage rate L may be tolerated for a time t before the compartment air conditions become just tolerable. If personnel are exposed for only one hour per week, the leakage rates may be approximately 100 times the leakage rates for continuous exposure.

To obtain actual values of allowable leakage rates from the curves, the ordinate values must be multiplied by $K \times 10^8$ and $K \times 10^8$ for Figs. 2 and 3, respectively, where

$$K = \frac{0.0283V}{\phi RG}$$

and V is the compartment volume expressed in cubic feet.

Periodic ventilation. If, instead of permitting no ventilation, the compartment is completely purged of its contaminated air periodically, the allowable leakage can be increased.

The allowable leakage is then

$$L = \frac{\lambda B}{\lambda N[1 - e^{-\lambda(t-t_a)}]} \times \frac{V}{\phi RG}$$

where t_a is the time after starting of operation that purging is effected.

Curves B and C of Figs. 2 and 3 show the effects of purging after 30 and 60 hr of operation. Curves for purging after longer periods will have similar shapes.

The analysis shows that for short periods of operation, the allowable leakage rates may be increased substantially, but that if periods between purgings are long this mode of operation is not satisfactory. This is evident because curves A, B, and C approach each other so rapidly.

Continuous compartment ventilation. If some of the radioactive particles be removed from the compartment air by filtering or by continuous ventilation, then the effective decay constant is increased and L increases.

We can set up the differential equation

$$\frac{dN'}{dt} = l - (\lambda + EF)N'$$

where EF is the fraction of radioactive particles removed per sec from the compartment air. Then

$$L = \frac{B}{N\lambda}\left[\frac{\lambda + EF}{1 - e^{-(\lambda+EF)t}}\right]\frac{V}{\phi RG}$$

where $(\lambda + EF)$ is the effective decay constant. For the case when filtering is used, EF is the product of the efficiency of the filter and the fraction of compartment air passed through the filter each second.

Figures 4 and 5 show how effective filtering or continuous ventilation is. Allowable leakage rates may be increased by as much as a factor of 100 over those shown in Figs. 2 and 3.

To find the required ventilation rate from the curves in Figs. 4 and 5, the expected leakage rate must first be multiplied by $1/(K \times 10^8)$ and $1/(K \times 10^{10})$, respectively. A value thus determined and the expected time of operation will then define a point on the curve sheet. If the point does not fall on one of the curves, interpolation can be easily accomplished.

Sample Calculation

Assuming the same coolant (water) and the corrosion products previously listed, the following hypothetical calculation demonstrates the use of the data presented.

With $\phi = 1 \times 10^{11}$ $n/cm^2/sec$, $G = 0.8$, $R = 0.1$, $V = 10{,}000$ ft³, estimated period of operation = 500 hr, and estimated coolant leakage rate = 1 cm³/sec, the number of cubic feet of air per minute required for ventilation on the basis of continuous exposure of personnel to contaminated air can be calculated.

The constant K is first determined by

$$K = 0.0283V/\phi RG = 0.354 \times 10^{-7}$$

Then the estimated coolant leakage rate is multiplied by $1/(K \times 10^8)$ and is

$$1/(0.354 \times 10^{-7} \times 10^8) = 0.282$$

In Fig. 4, 0.282 on the ordinate and 500 hr on the abscissa give the required ventilation rate as approximately 0.01 ft³ of air per min per ft³ of compartment air volume.

Therefore, the required ventilation rate is $0.01 \times 10{,}000 = 100$ ft³ of air per min.

* * *

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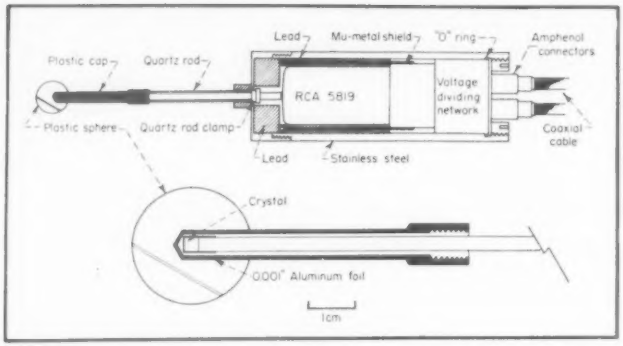

FIG. 1. Cross section of the scintillation counter with detail of the detecting element

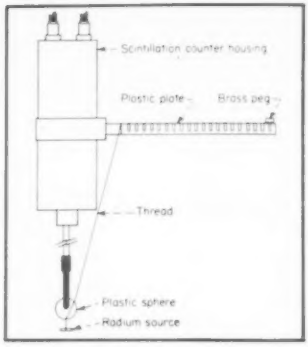

FIG. 2. System used to vary distance between source and detector

Comparison of Air and Tissue Doses for Radium Gamma Rays

The equivalence between air and tissue doses has been investigated by means of water phantoms and a scintillation counter. The air-to-tissue-dose ratio is greater than unity, independent of phantom size in the volume range from $(10cm)^3$ to $(60cm)^3$

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THE DISTRIBUTION of gamma-ray intensity as a function of the distance in air from a filtered radium source was determined in 1933 by Griffith (*1*). He also studied the alterations of this distribution when the air was replaced by water phantoms of various sizes. His results indicated that up to a distance of 8 cm in a 31 × 19 × 19-cm phantom, and 12 cm in a 60 × 60 × 60-cm phantom, the intensity of the gamma radiation was the same in air as in water. Compensation of absorption loss in water by scatter presumably accounts for these results.

The radiation detectors used by Griffith were metal ionization chambers of varying volume and composition. The conclusion that the gamma-ray intensity up to distances of 10 cm from the source was independent of the medium in which the measurement was made was based on measurements made with an "electron-metal" chamber (92.9% Mg, 3.4% Al, 3.3% Zn, 2% Cu, and a trace of Pb).

The present work was undertaken to ascertain the validity of Griffith's results when a scintillation counter is used as the radiation detector.

The detecting element of the scintil-

* Fulbright Fellow from the University Fuad I, Cairo, Egypt.

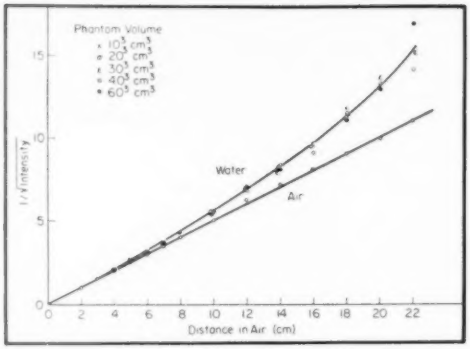

FIG. 3. Variation of $1/\sqrt{I}$ for different phantoms as a function of the distance in air

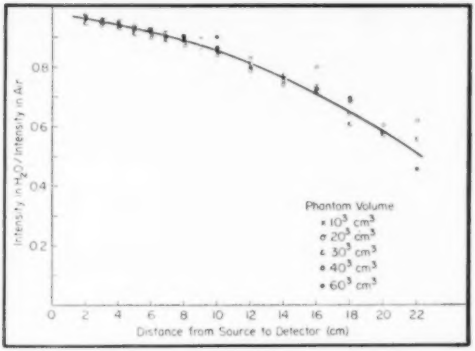

FIG. 4. Ratio of gamma-ray intensity in various phantoms to that in air as a function of the distance between source and detector

lation counter, shown in Fig. 1, is a cylindrical anthracene crystal 3.5 mm in diameter and 4 mm high. This crystal is cemented to the end of a cylindrical quartz rod ⅛ in. in diameter and 30 cm long. The crystal is surrounded by a 0.001-in.-thick aluminum foil, and by a 0.5-mm-thick hard rubber cap. The extremity of the hard rubber cap is fitted with a Lucite sphere 1 in. in diameter.

The quartz rod is contained in a stainless-steel tube attached to the light-tight stainless-steel housing of the 5819 photomultiplier tube. This housing also contains a voltage divider for the photomultiplier, a magnetic shield, and some lead shielding in front of the photocathode of the photomultiplier. The photomultiplier is operated at about 100 volts per stage, regulated to about 0.1%. The current flowing through the tube is measured with a vacuum-tube microammeter (modified RCA WV84A) (*2*).

A 40-mg radium source, filtered by 0.5 mm of platinum, was used in these measurements. It was housed in a cylindrical capsule 3 mm in diameter and 1.7 cm long.

The device used to vary the distance between detector and source is shown in Fig. 2. The radium is attached to a fine thread that passes through a guide drilled in the plastic sphere. This thread is fixed to a brass peg which can be fitted into one of a series of holes drilled 1 cm apart in a plate that is attached to the housing of the photomultiplier. A surgical serum and moisture-proof Ethicon suture No. 40 is satisfactory for use as a thread; it shows no appreciable shrinkage or stretching when dipped in water.

The scintillation counter is attached to an X-ray stand that allows a vertical motion of the instrument of about 60 cm. This structure permits the detector and source to be put in water with a minimum disturbance of their relative position.

Five cubical plywood boxes filled with water were used as phantoms. The volumes were, approximately, $(10\text{cm})^3$, $(20\text{cm})^3$, $(30\text{cm})^3$, $(40\text{cm})^3$, and $(60\text{cm})^3$.

Measurements

For the measurements, the radium source was brought against the plastic sphere that surrounds the detecting element of the counter. The voltage across the photomultiplier was adjusted for a tube current of about 90 μa. Then, without any change in the respective position of the crystal and source, they were immersed in the water phantom, and the reading of the microammeter recorded. This procedure was repeated several times.

The peg that holds the thread was then moved 1 cm, and the measurements in water and air were repeated for the new position of the source. These measurements were carried out up to a distance of 4 cm. The voltage on the photomultiplier was then readjusted to give a high reading on the microammeter, and readings were taken from 4 cm on.

All the readings for the phantoms were taken in such a fashion that the center of the line joining the source and the crystal coincided with the center of the phantom. The measurements were carried out for each of the five phantoms.

Results

The results of the measurements are shown in Figs. 3 and 4. In Fig. 3, the term intensity is taken to be a measure of the rate of absorption of gamma rays in the anthracene crystal.

The air measurements are corrected for the amount of radiation absorbed in the plastic sphere that surrounds the detector. The correction was determined by using the known gamma spectrum of RaB + RaC (*3*), and determining the fraction of each of the components transmitted through 0.5 mm of platinum and 1 cm of Lucite.

The distance between the crystal and the source for the first position was determined by extrapolating the air curve of Fig. 3 to zero. The distance thus found was 2 cm.

Within the experimental errors, the results shown in Figs. 3 and 4 indicate

1. That the air dose, when the distance from the source is 2–22 cm, differs from the phantom or tissue dose.

2. That the water-to-air-dose ratio is independent of the size of phantom between $(10\text{cm})^3$ and $(60\text{cm})^3$.

Air Equivalence

Comparison between Griffith's curves and the results reported here shows some discrepancies well beyond the experimental error. The explanation should be found in the experimental methods used. Probably the most debatable aspect of the present experimental setup is the use of a

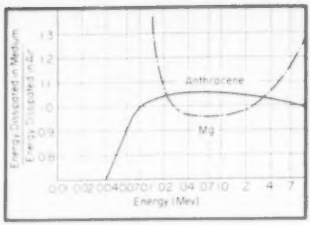

FIG. 5. Ratio of energy dissipated in magnesium and anthracene to that in air as a function of the gamma-ray energy

scintillation counter as an air-equivalent radiation detector.

The linear relation, in a scintillation counter, between the energy dissipated in the crystal by electrons or gamma rays, and the intensity of the electric current flowing through the photomultiplier has been well established (*4, 5*).

The detecting element of the counter used in the present work is a small anthracene crystal cemented to a quartz rod and surrounded by a 0.001-in. aluminum foil, a 0.5-mm hard rubber cap, and a 2.5-cm-diameter Lucite sphere. The purpose of the aluminum foil is to increase the light gathering power of the system. The hard rubber cap is a light-opaque shield. The Lucite sphere prevents any secondary electrons generated outside the system from reaching the detector. Both the Lucite sphere and the hard rubber cap are nearly air equivalent in the energy range considered.* Neither the aluminum foil surrounding the crystal nor the quartz rod which is in immediate contact with it seem to alter appreciably the air equivalence of the crystal (*2*).

Therefore, the air equivalence of this scintillation counter will depend on the air equivalence of the anthracene crystal, over the energy range to be covered. The energy of the gamma rays from RaB + RaC ranges between 243 and 2,219 kev, with an effective energy of about 800 kev. In air, the multiple scattering is small and the energy shift relatively unimportant. In water, however, multiple scattering becomes important, and the effective energy is appreciably lowered.

According to Wilson (*6*), the effective wavelength of the gamma radiation emitted by an uncollimated radium source surrounded by water is, at 10 cm, about 35 X units, which corresponds to about 350 kev. At greater distances from the source, this energy does not seem to be reduced appreciably. It is necessary, therefore, to study the air equivalence of anthracene between about 300 and 1,000 kev.

Figure 5 shows the ratio of the gamma-ray energy dissipated in a medium to that dissipated in air, as a function of the energy of the radiation. The energy dissipated is given by

$$\frac{\tau}{\rho} + \frac{\sigma_a}{\rho} + \frac{\kappa}{\rho}$$

where τ is the photoelectric absorption coefficient, σ_a is the Compton absorption coefficient, κ is the pair production absorption coefficient, and ρ is the density of the medium.

In Fig. 5, the curve labeled anthracene is actually for a medium with the composition C_6H_5, which is a close approximation to the composition of anthracene ($C_{15}H_{10}$). The curve was determined on the basis of the absorption coefficients of C, H, O, and N. The ratio does not vary by more than 3% between 150 and 3,000 kev, and by less than 1.5% between 300 and 2,000 kev.

To the knowledge of the authors, the air equivalence of anthracene has not yet been investigated experimentally over this range of energies. However, Smeltzer (*7*) has investigated the energy dependence of a naphthalene scintillation counter, and found that between 200 and 1,200 kev this detector is air equivalent within 1.5%. The atomic composition of naphthalene ($C_{10}H_8$) is sufficiently close to that of anthracene to apply Smeltzer's results to the latter. On the basis of the above discussion, it appears that anthracene is air equivalent within 2% over the energy range under consideration.

It is possible to account for the discrepancies between the results noted in this paper and those reported by Griffith, by calling attention to the setup used in the earlier work.

1. In the earlier work, the ionization chambers had a total volume of about 335 mm³, which made distance determination difficult. In the present setup, the anthracene crystal has a volume of 40 mm³.

2. In the earlier work, the thickness of the chamber walls was insufficient to stop all the secondary electrons coming from outside the chamber, namely those created in the platinum that surrounds the radium. This effect would tend to lower the water-to-air intensity ratio at short distances, which would diminish the discrepancy between the results under discussion.

3. The great majority of the secondary electrons which account for the ionization in the electron-metal-wall chambers were formed in the electron metal (mostly magnesium). The air equivalence of magnesium over the energy range under consideration is shown in Fig. 5. Magnesium is air equivalent within about 2.5% between 300 and 2,000 kev. However, if the lower limit of this energy range is lowered to 200 kev, the deviation is as high as 11%. This might explain the discrepancies because it is conceivable that, in water, an important fraction of the gamma radiation may be shifted to this low energy. This would tend to increase the water readings, and bring them closer to the air readings.

* * *

The authors wish to thank Dr. G. H. Fletcher of the University of Texas, M. D. Anderson Hospital, Houston, Texas, for his very stimulating discussion of this problem.

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* The discussion of this point is very similar to that which follows for anthracene.

No Index This Month . . . .

In the past, NUCLEONICS has published two volumes a year, with indexes appearing in the June and December issues. With the new enlarged format, NUCLEONICS will have only one volume per year. The index for volume 10, January to December, 1952, will be published in the December issue.

FIG. 1. Multiple trace record of afterpulses. Maximum of envelope of the peaks is at 1 μsec

Afterpulsing in Photomultipliers

Spurious counts can be caused in scintillation counting by photomultiplier afterpulsing. Data from Los Alamos shows that afterpulsing has an early and a late component; the latter is eliminated in tubes with a shielded structure. An experimental tube shows no afterpulsing, but its response is poor

By DONALD W. MUELLER, GEORGE BEST, JASPER JACKSON, and JOHN SINGLETARY
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AT LOS ALAMOS, afterpulsing was first recognized as an important defect of the scintillation counting technique by Lanter and Corwin.* They used 4×10^{-8} sec wide, 75-kv X-ray pulses and observed small associated pulses following the main pulse from the photomultiplier tube. Later, they used single scintillations from stray radiation for similar observations. Harrison, Godfrey, and Keuffel† of Princeton have also reported on "Satellite Pulses from Photomultipliers."

The integral effect of the phenomenon came to our attention in connection with application of a gate to the first dynode of a 5819 photomultiplier. R. C. Winterbottom and M. V. Harper conducted this experiment with steady illumination and gated the multiplier

* R. J. Lantner, R. W. Corwin, *Rev. Sci. Instr.* (To be published).

† F. B. Harrison, T. N. K. Godfrey, J. W. Keuffel, *Phys. Rev.* **84**, 1248 (1951).

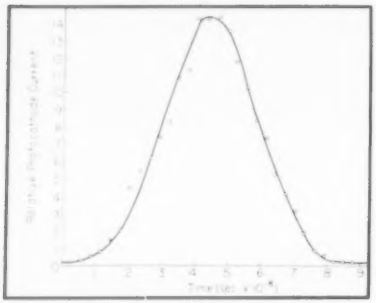

FIG. 2. Expected light intensity as a function of time for rotating-mirror light pulse for mirror speed of 1,000 rps

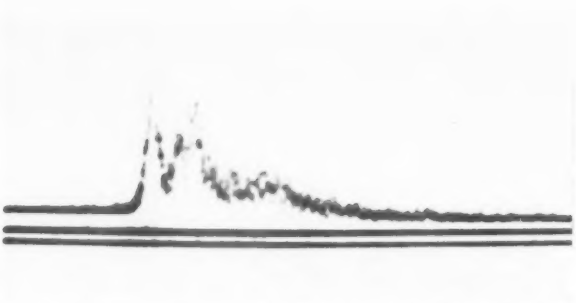

FIG. 3. Slow-response components of 5819 photomultiplier to light pulse shown in Fig. 2. The main pulse is off scale, and the first sharp peak occurs at about 1 μsec. A second broad maximum is indicated at about 3 μsec

off by swinging the dynode adjacent to the photocathode 8 volts negative with respect to the photocathode. Although the gate had a 0.1-μsec decay time, a noticeable tail persisted on the anode signal for about 1 μsec beyond the effect of the gating disturbance. The magnitude of the residual tail varied noticeably among different tubes.

The integral effect became more apparent with the use of a Tektronix 517 oscilloscope and a 75-kv X-ray step function. We observed that the output failed to follow the X-ray step by about a 5% residual at 0.25 μsec after the gating-off. We used terphenyl in toluene as a scintillator. At low gains, ranging from 3,000 to 16,000, there was no obvious change with gain in the percentage of this residual. The percentage increased at high gains.

Afterpulsing is easily observed with a fast phosphor such as terphenyl in toluene, with a 5819 photomultiplier and a Tektronix 517 oscilloscope. There is a copious supply of background pulses, and the apparatus is set to trigger on signal from these pulses with a sweep speed of about 2 cm/μsec. Figure 1 shows a multiple sweep record with many afterpulses superposed. This figure shows a marked grouping of the afterpulses at about 1 μsec. The main pulses are superposed and represented by the tall peak at the extreme left. In the experiments of Lanter and Corwin, this maximum occurs at about ½ μsec.

We made observations on the size of afterpulses at low gain. Records were first obtained by triggering the 517 oscilloscope on signal from background scintillation pulses. Subsequently, and maintaining the same dynode voltages, the scintillator was removed and the photocathode illuminated with a small amount of light sufficient to give several pulses per sweep, these pulses presumably being due to single photoelectrons from the cathode. The sweep was triggered with an externally generated signal. Comparison of the records indicated that the afterpulses were about the same height as, or slightly taller than, the light pulses. Corwin and Lanter, however, have made observations at higher gain and report afterpulse heights corresponding to more than one photocathode electron and a dependence upon the height of the main pulse.

Observations of afterpulses from scintillations were carried out at room temperature, at liquid nitrogen temperature, and at liquid helium temperature. No marked change in the amount of afterpulsing was observed. In these experiments the photocathode end of the glass envelope was immersed in the liquid nitrogen or helium for about 15 minutes.

We now have a rotating-mirror device in operation which produces a short and relatively intense light pulse or, alternatively, a sharp-edged step function. The shape of the light pulse as expected for a mirror speed of 1,000 rps and a particular set of narrow slits is shown in Fig. 2. This shape was deduced from static measurements of photocathode current as a function of angular position of the mirror. Peak photocathode currents in the 0.3-μa range are obtained with an average 5819 tube and an incandescent light source; the use of a high-pressure mercury arc gives currents that are higher by a factor of 10.

The system can be operated to produce a continuous display of the response on a Tektronix 517S oscilloscope. The delayed response appears as a relatively continuous curve, due to the large number of photoelectrons in the primary pulse. Figure 3 shows a single-sweep 5819 record taken with this apparatus and the same slit system as that used for the data of Fig. 2. In this case the output was taken from the ninth dynode. The main pulse goes off scale and a major slow component peak occurs at about 1 μsec; a second peak is also indicated at about 3 μsec. The total area of the slow component relative to the main peak is of the order of 3% for a good 5819 tube.

The relative magnitude of the fast and slow component is more easily demonstrated by a rectangular light pulse. For this purpose a wide exit slit was used on the rotating mirror. The driving light function in this case is flat-topped and 5 μsec wide, the 10 to 90% rise time being about 3×10^{-8} sec. Figure 4 shows the response of a relatively poor 5819 photomultiplier to this step function. Note the residual after the light goes off.

Figure 5 shows the excellent response of an experimental tube, C-7151-B, furnished to us by Radio Corporation of America, Lancaster, Pa. This tube has silver-magnesium dynodes and was subjected to thorough outgassing. The photocathode sensitivity of this

tube, however, was below that of an average 5819 by a factor of seven per unit area.

In an attempt to determine the source of the afterpulses, the photocathode and first-dynode currents of 5819's were measured with normal voltages applied to the dynodes and a steady source of light. Then the tube was biased essentially to cut off at the sixth dynode, and the currents were measured again. There was a decrease of from 2 to 5% in the cathode current and of 5 to 10% in the first-dynode current under the latter conditions. R. G. Stoudenheimer, RCA, Lancaster, subsequently observed that this effect is more pronounced if the second measurement is made with all dynodes tied together. This effect is interpreted as indicating that there is feedback to the cathode which might be related to the afterpulses. This is further substantiated by an experimental 5819 furnished by RCA, Lancaster, which had a shield completely surrounding the dynode structure and tied to the first dynode. In this tube the delayed response beyond about ¼ μsec was eliminated. However, some delayed effect was observed within about ¼ μsec of the main pulse.

* * *

This article was presented at the Scintillation Counter Symposium, Washington, D. C., January 29, 1952. The work described was done under the auspices of the U. S. Atomic Energy Commission.

FIG. 4. Response of poor 5819 photomultiplier to rectangular light pulse 5 μsec wide. The clean-edged driving function has a rise time of 3×10^{-8} sec. Compare Fig. 5, for which the same driving function was used

FIG. 5. Excellent response of RCA experimental tube C-7151-B to the same 5-μsec-wide rectangular light pulse as used for preceding figure

Electronic Peak-Reading Kilovoltmeter

AN INSTRUMENT that accurately measures the high voltages associated with X-ray equipment has been developed by R. E. Brueckman of the National Bureau of Standards, Washington, D. C. The unit is designed to indicate directly peak voltages between 30,000 and 125,000 volts. It replaces the sphere-gap method and is especially useful for measuring voltages during short exposures.

The actual circuit consists of eleven 2D21 thyratrons, each having an indicating neon light in its plate circuit. The critical bias on these tubes is about −3 volts at plate potentials of about 150 volts. With a bias voltage of 103 volts, for example, the tube will fire when the drop across two 50,000-ohm resistors between the bias cell and ground and the cathode and ground reaches 100 volts. These two resistors form part of a two-section voltage divider across the X-ray tube.

The grids of the thyratrons are biased in 1-volt increments by potentiometers in each grid circuit. Twenty series-connected resistors are connected to a 22-position selector switch so that a voltage from 30 to 125 volts in 5-volt steps can be added to the bias on each tube. These resistors and the potentiometers constitute a voltage-dividing network to which 150 volts d-c is applied.

It is thus possible to preset the instrument to read the kilovoltage within any desired 10-kv range, the reading being the sum of the setting on the coarse selector switch and the number indicated by the last activated neon lamp. Calibrating circuits are included in the instrument.

During normal operation, the meter draws a maximum current of 1.25 ma from the X-ray equipment. A time delay circuit made up of two thyratrons and relays can be used to prevent recording the initial voltage surge during short exposures.

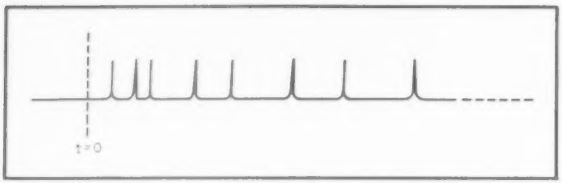

FIG. 1. Random time distribution of scintillation photoelectrons from a single event. Spacing is closest near $t = 0$

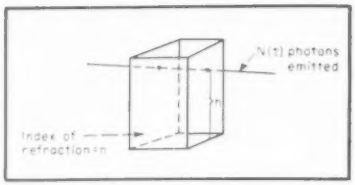

FIG. 2. Schematic representation of particle passing through crystal or light pipe

Resolving Time of Scintillation Counters

Statistical analysis indicates that the limiting resolving time now obtainable is 3×10^{-10} sec. Light pipes of moderate length can double the resolving time, according to calculations based on a solution to the optical problem of the time-intensity distribution of scintillations that are transmitted

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STATISTICAL FLUCTUATIONS associated with the emission and collection of photons from a scintillator limit the attainable resolving time of the scintillation counter. These fluctuations and their effects are discussed here.

Consider first the problem of calculating the ultimate speed of a scintillation counter in which all broadening effects due to the photomultiplier and succeeding circuits have somehow been removed. In such a case all scintillation counts, presented on a time axis, would appear somewhat as shown in Fig. 1. Some time after the excitation of the scintillator ($t = 0$), fluorescence photons are emitted and eventually collected at the photocathode. A small, randomly selected, number of these photons eject photoelectrons from the multiplier photocathode. After multiplication these appear as individual pulses as shown. On the average, these pulses will be closest spaced in time near $t = 0$, and thereafter their average frequency of occurrence will diminish with the scintillator decay time. However, apart from this general widening, it is apparent that their spacing will be random, and this randomness will introduce an inevitable time uncertainty into the measurements.

To convert such a signal into a measurement of the time $t = 0$, some feature of the received signal must be used as a marker from which to measure time. Stripped to its essentials, the problem can be stated as follows: If for each scintillation count it is possible to measure precisely the time of emission of one of the photoelectrons, say the Qth one (after the passage of a particle through the scintillator), within what limits does this time fluctuate with respect to time $t = 0$?

This statement of the problem is a realistic one for weak events in slow scintillators, when the individual photoelectron pulses *can* be resolved in time. For energetic events in fast scintillators, however, it is not possible to resolve the individual photoelectron counts with presently available multipliers. In this case, choosing the Qth photoelectron as a marker corresponds approximately to setting some pulse-height discriminating circuit to trigger at a given pulse height—reached after the integration (overlapping) of Q amplified photoelectrons. In this case there will be an additional uncertainty

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introduced because the value of Q at which the discriminator triggers is not precisely defined. This will introduce an additional indeterminacy in the timing.

It should be carefully noted that the resolving-time limitations discussed here take the form of a fundamental uncertainty in defining a time of occurrence. Any attempt to refine the electronic counting circuits to a resolving time shorter than this time will result not only in reaching a limiting conventional "resolving time" not shorter than these uncertainties, but will also result in an unavoidable loss of counts, so that in the limit of perfect multiplier and coincidence circuits, the counting efficiency must approach zero.

Statistics of Fluctuations

The problem of calculating the statistical fluctuations in the arrival time of the Qth photoelectron is a straightforward one in statistics. The general solution to this problem for an arbitrary light emission and collection function, $f(t)$, has been published [R. F. Post, L. I. Schiff, *Phys. Rev.* **80,** 1113 (1950)]. As an example, consider the case of the exponentially decaying scintillator, for the moment neglecting light-collection delay effects. If $N(t)$ photons are emitted by the scintillator, then a small fraction $f(t)$, on the average, are converted to photoelectrons, with

$$f(t) = R(1 - e^{-\lambda t})$$

R is the *average* total number emitted, and $f(t)$ thus describes the *average* number of emitted photoelectrons as a function of the time. The average *rate* of emission is

$$df/dt = R\lambda e^{-\lambda t}$$

proportional to the product of R and the decay constant λ.

In this case the solution for the fluctuation time, Δt, in the arrival of the Qth photoelectron takes the asymptotic form ($R \gg 1$)

$$(\Delta t)^2 \approx \frac{Q}{(R\lambda)^2}\left[1 + \frac{2(Q+1)}{R} + \cdots\right]$$

It is to be noted that Δt depends primarily on the initial rate of photon emission, $R\lambda$, and not on the number R, so that those scintillators with the largest value of $R\lambda$ are best suited to fast counting. To take a practical case of a fairly large event in a scintillator such as terphenyl in toluene,

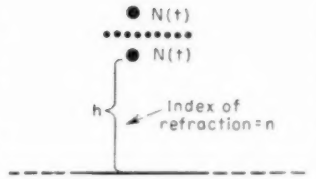

FIG. 3. Representation of equivalent point light source and its image above an infinite plane

typical values are $Q \approx 25$ and $R = 75$. The decay constant, λ, has been determined by several investigators to be about 4×10^8 sec^{-1} ($1/\lambda = 2.5 \times 10^{-9}$ sec). Thus the time indeterminacy is $\Delta t \approx \pm 2.5 \times 10^{-10}$ sec.

This is optimistic, since Q usually is not defined precisely for any given measurement, as discussed previously. The possibility of reaching $Q = 1$, where Δt takes its smallest value, is discussed later.

Optical Effects

What effect, if any, will the optical phenomena occurring in the transmission and collection of the light play in the ultimate time uncertainty? It is apparent that transmission and collection will reduce the rate of photon arrival at the photocathode compared to the idealized example given previously, since the light arrives at the photocathode after successive reflections inside the scintillator and light pipe, if one is used. Thus, from the qualitative behavior of the previous solution, it can be seen that Δt will be increased.

It turns out that as far as *time effects* are concerned, a rigorous solution of the optical problem of the crystal or light pipe may be constructed by a simple device. This method of solution is undoubtedly a very old one, but the author has been unable to find prior references to it.

Consider a rectangular parallelopiped of arbitrary dimensions. A particle is assumed to pass through this figure parallel to the top surface at a distance h above the bottom surface, as shown in Fig. 2. Now if each surface except the bottom one is perfectly reflecting, and the bottom surface (located at the photocathode) is transparent, the intensity–time distribution of the light passing through the bottom surface can be shown to be precisely equivalent to that found for an isotropic point source (and its image in the upper surface) located above an infinite plane, where now we ask for the time of arrival of the photons at the infinite plane (Fig. 3). The time distribution of the point sources is to be the same as that of the original fluorescent track, namely $N(t)$. The equivalence of the two cases (valid also for a cylindrical light pipe of arbitrary cross section) is based on the physical fact that the downward component of velocity of any initial ray is unchanged by reflection in an arbitrarily located vertical surface.

The solution of the optical time–intensity problem for any $N(t)$ can now be simply obtained. Departure from perfect reflectivity, which may occur for rays past the critical angle for total internal reflection, will reduce the incident light somewhat, but will in general only affect the longest delayed components. This can be allowed for.

When $N(t)$, the original light pulse, takes place near the top of the pipe and is of negligible duration (for example, if it is due to diffused Cerenkov radiation, with neglect of the particle transit time), then the solution for the light pulse at the bottom of the light pipe takes on a particularly simple form

$$\frac{dN}{dt} = \frac{N_0}{t_0}\left(\frac{t_0}{t}\right)^2 \quad t \geq t_0$$
$$= 0 \qquad\qquad t < t_0$$

where N_0 is the total number of photons emitted initially, and t_0 is the time of transit of the first photon to reach the bottom of the pipe. Departure from perfect reflectivity beyond the critical angle will result in a reduction of the light flux for $t > nt_0$, so that some of the (late) photons will be absorbed, reducing the total light flux by perhaps 30% in a typical case.

In this example, even though the initial rate of light emission at the particle track approaches infinity, the light flux at the bottom of the pipe is quite finite, being reduced to a maximum value of N_0/t_0 and thereafter decaying inversely as t^2. It follows that if the actual initial light pulse has a finite rate at $t = 0$, as is the case for the exponentially decaying light pulse considered earlier, then at $t = t_0$, df/dt must be zero, thereafter increasing linearly, reaching some maximum value, and then decaying with the characteristic decay time of the scintil-

lator. Qualitatively, df/dt would look something like Fig. 4, so that $f(t)$ would have the qualitative appearance of Fig. 5.

Reduction of df/dt near the origin will increase Δt. If $t_0 \ll 1/\lambda$, the increase will be negligible for presently accessible resolving times, but for a light pipe where t_0 is comparable to $1/\lambda$ (h of the order of 10 cm or more for terphenyl in toluene), the collection-time spread will appreciably increase Δt.

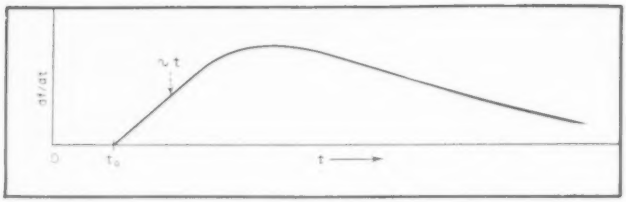

FIG. 4. Average rate of photoelectron emission plotted qualitatively as function of time

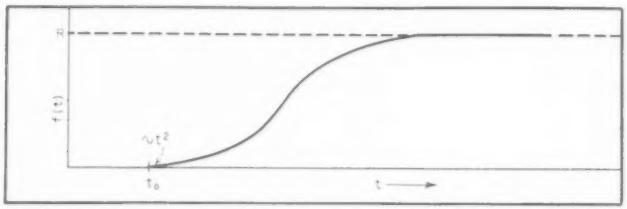

FIG. 5. Average number of photons converted to photoelectrons plotted qualitatively as function of time

Light-Pipe Delay

The exact calculation of the general solution for the case described here, where both light-collection effects and scintillator decay are exactly represented by $f(t)$, is comparatively difficult. It is, however, possible to obtain an exact solution for a particular functional form of $f(t)$, which can be made to approximate the actual $f(t)$ quite well in certain cases. If $f(t)$ is taken to have the form

$$f(t) = \frac{R\left(\frac{t}{t_0}\right)^2}{\alpha + \left(\frac{t}{t_0}\right)^2} \quad t > 0$$

it can be shown that by properly choosing the parameter α, both $f(t)$ and df/dt will have the correct behavior near $t = 0$ (as compared with an expansion of the exact $f(t)$ about this point). Here $t = 0$ is taken to be measured from the time of arrival of the first photon at the photocathode. Also, it can be seen that $f(t)$ has roughly the right asymptotic behavior for t large. Strictly speaking, the form of $f(t)$ chosen is not "well behaved" for $t \to \infty$, so that the series solution obtained is an asymptotic one.

Thus the function chosen should be expected to give reasonably reliable results when used to calculate Δt. The asymptotic series for Δt in this case is

$$(\Delta t)^2 = \frac{\alpha t_0^2}{R}\left\{Q\left[1 + \frac{(Q+1)}{R} + \frac{(Q+1)(Q+2)}{R^2} + \cdots\right] - \left[\frac{\Gamma\left(Q+\frac{1}{2}\right)}{\Gamma(Q)}\right]^2\left[1 + \frac{\left(Q+\frac{1}{2}\right)}{2R} + \frac{(1)(3)\left(Q+\frac{1}{2}\right)\left(Q+\frac{3}{2}\right)}{(2)(4)R^2} + \cdots\right]\right\}$$

If this solution is evaluated for the case $t_0 \approx 1/\lambda$, where it should be quite good, it can be shown that α should have the value e, 2.72. Evaluating Δt above, for $Q = 25$, $R = 75$, $t_0 = 1/\lambda = 2.5 \times 10^{-9}$ sec, we find $(\Delta t) \approx 5 \times 10^{-10}$ sec, so that the effect of a perfectly reflecting light pipe about a foot long is to about double the time uncertainty. Departure from perfect reflectivity will increase Δt correspondingly.

Since time uncertainties Δt, as calculated here, will appear in both channels of any coincidence circuit operated from the counters, then the conventional resolving time of the coincidence circuit will be approximately at least $\sqrt{2}$ times as broad as the times calculated here, or about 7×10^{-10} sec in the previous example. The uncertainty in the value of Q at which an impulse is recorded (introduced largely by the circuit used and by the photomultiplier) will also add to the broadening. It can be seen that an appreciable deterioration in resolving times is to be expected when light pipes of moderate length are used.

Limit of Resolution

In conclusion, one can summarize the results of these calculations by making educated guesses as to the limit of resolution of the scintillation counter with presently known scintillators. So long as photomultipliers are not capable of resolving the individual photoelectron pulses, the desirable case $Q = 1$ is not accessible. Thus if no light piping is used, it appears that for events of usual size (approximately 1 Mev lost in the scintillator) resolving times better than about 3×10^{-10} sec cannot be achieved. When light pipes of even a few centimeters in length are used, this figure must be appreciably increased.

With improvement in the photomultiplier to the point where the case $Q = 1$ may be distinguished with certainty, an improvement of the order of three or more might be in sight. With the use of Cerenkov radiation as a light source, the calculations indicate an order of magnitude of improvement is possible, provided a photomultiplier capable of such resolution is then available.

Qualitative verification of the effects of scintillator statistics on resolving times, and the broadening due to the use of light pipes, seems to have been obtained by various groups using scintillation counters in high-resolution coincidence measurements. There has not as yet been any careful quantitative investigation of these effects as far as is known.

* * *

This article was presented as a discussion at the Scintillation Counter Symposium, Washington, D. C., January 30, 1952. The work was supported in part by the Office of Naval Research and in part by the U. S. Atomic Energy Commission.

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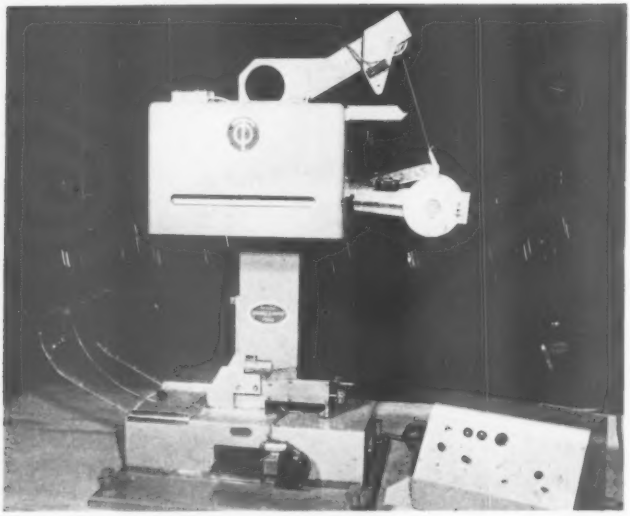


Remotely-Operated Impact Tester

By W. PATE, E. HUTTO, and E. MARGUERAT
Engineering Department, Oak Ridge National Laboratory
Oak Ridge, Tennessee

Recently, the problem of remote operation of an impact tester was posed by the Solid State Division at the Oak Ridge National Laboratory.

The operations that are involved in remote operation of an impact tester, and in handling radioactive test specimens through a 3-ft wall are:

1. The hot sample has to be picked up from its shielded container and placed in correct position in the jaws of the impact tester vise.
2. The sample has to be clamped in the vise in this position.
3. The pendulum has to be released from its latched position.
4. After the specimen has been broken, the pendulum has to be returned to its latched position.
5. Half of the sample that is broken must be contained and not be allowed to fly across the enclosure after the impact of the pendulum.
6. The other half of the specimen, which is held clamped in the jaws of the vise, must be released and placed in position to be readily picked up by a general-purpose manipulator tong.

Briefly, the objective of the Izod and the Charpy impact tester is to determine the toughness of a specimen material. The impact is furnished by the swing of a pendulum of known weight. The energy supplied by the pendulum is the product of its weight and the height of fall; the energy left after fracture of the specimen is the product of its weight and the height of its rise. The difference is the energy required to break the specimen.

The altered impact tester is shown in the figure. In altering this impact tester for remote operation, it was found that the impact head and supporting arms were delicately balanced dynamically by the manufacturer. Hence, it was not advisable to alter directly these parts of the machine for remote control.

The alterations which were made to the impact tester for carrying on the testing operations remotely are:

1. General-purpose remotely controlled tongs are used to place the specimen in the vise.
2. For clamping the specimen, the vise was altered for remote control. The vise screw is driven by a remotely controlled fractional-horsepower motor. The motor pivots on its axis to contact a cutoff switch after a predetermined clamping load is applied by the vise. This arrangement insures uniform and predetermined vise gripping pressure, regardless of the thickness of the specimens. It also insures that the motor will break the tightened screw position because it will initially come up to speed on the return swing on its axis before actually propelling the vise screw.
3. A solenoid-operated trigger has been added to release the pendulum.
4. After the specimen has been broken by the pendulum, a long period is normally required for the pendulum to come to rest. For this reason a special reset arm was designed to catch the pendulum while in motion, and return it to its latching position. The special reset arm is pivoted on a hollow pin supported on bearings mounted in the frame of the testing machine on the same center of rotation as the pendulum. It is actuated by a motor drive with a variable-pitch pulley to give constant load and maximum efficiency. This permits the use of a minimum size motor.
5. A plastic box with rubber strips was added to catch the half of the broken sample so that it could be readily picked up by the tongs.
6. A conveyor with motor drive was installed in the base of the machine just under the vise. When the jaw of the vise is released, the other half of the specimen drops to the conveyor. The conveyor brings the sample out and deposits it in a position to be picked up readily by the manipulator tongs.

All controls are equipped with limit microswitches to prevent any damage to the machine by overriding, etc. A control box with all the necessary controls and indicator lights is placed in a convenient location on the nonradioactive side of the barrier wall.

Automatic Tester for G-M Tubes

By G. H. STREIT and W. R. KENNEDY
Atomic Energy Project, School of Medicine
University of California at Los Angeles
West Los Angeles, California

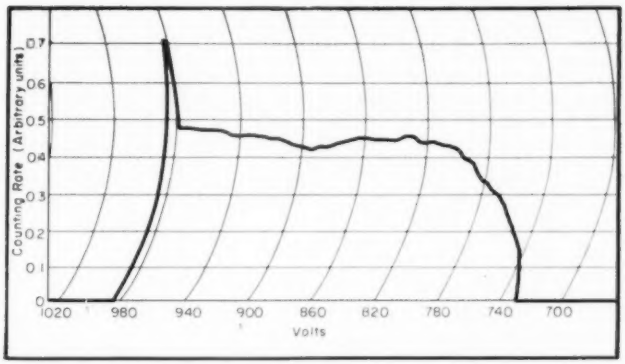


FIG. 1. Curve obtained for a type 1B68 G-M tube

An instrument has been developed which automatically traces the curve of counting rate versus potential for a variety of G-M tubes. Data can be obtained for the starting potential, threshold, plateau, and beginning of the continuous-discharge region.

The system for obtaining the data is essentially a sawtooth generator for applying an increasing voltage to the G-M tube, and a means for measuring the counting rate. The counting rate is presented along the ordinate of an Esterline-Angus recorder, and the voltage is presented along the usual time scale.

The instrument can sweep two voltage ranges, one about 700–1,000 and the other about 900–1,500 volts. Considerable departures from these limits are available through suitable controls.

The circuit for the instrument is shown in Fig. 2. A record of a 1B68 tube used with a radium source is shown in Fig. 1.

The negative G-M tube pulse is integrated in the output of the trigger circuit, V_1 and V_2, to measure the counting rate, which is registered on the Esterline-Angus recorder in the integrator circuit. If the counting rate rises above a preset value, relay RY_1 opens and the voltage across the G-M tube is reduced to a safe value.

The instrument has three power

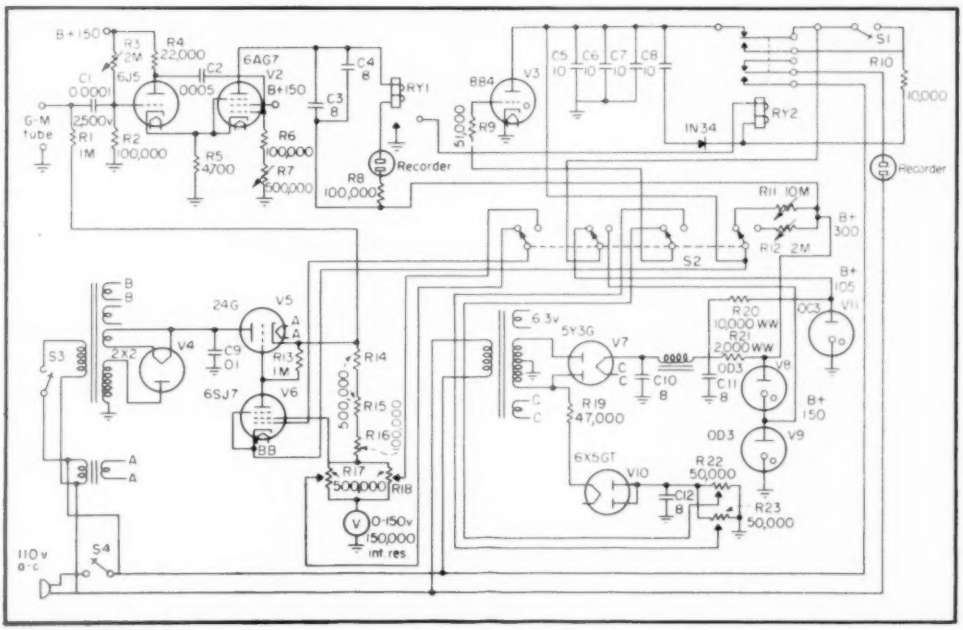


FIG. 2. Circuit diagram for the automatic Geiger-Müller tube tester

supplies: V_4, V_5, and V_6 provide regulated high voltage for the G-M tube; V_7, V_8, V_9 and V_{11} provide B+; and V_{10} provides bias voltage.

The high-voltage sweep is obtained by replacing the usual gas reference tube in the cathode of the shunt tube, V_6, by the type 884 thyratron, V_3, which with its associated circuit makes up a sawtooth generator. In the quiescent state, before the start of the voltage sweep, the cathode of V_6 is held at either 105 or 150 volts by V_9 or V_{11}, which are a part of the B+ supply to the thyratron. A panel meter in series with R_{14}-R_{18} is used to measure the high voltage.

The starting voltage for the G-M tube voltage sweep is determined by R_{17} or R_{18}. Separate controls in the grid circuit of V_6 determine the two independent starting voltages, which can be varied over a wide range by adjustment of R_{17} or R_{18}. The maximum of the high-voltage sweep is determined by the settings of R_{22} or R_{23}, and these determine the voltage at which the thyratron fires. Two independent controls are used here also to accommodate the low and high voltage ranges. A maximum of 300 volts, obtained from V_8 and V_9 in series, can be applied to the anode of the thyratron.

Thyratron holding voltages of either 105 or 150 volts, obtained from V_9 or V_{11}, are connected to the thyratron anode through the contacts of relay RY_2. The 300-volt B+ is connected to the thyratron anode through R_{11} or R_{12}. The voltage drop across these resistors is such that the constant voltage drop across V_9 or V_{11} determines the thyratron anode potential. Momentary closing of switch S_1 energizes RY_2. This disconnects the source of 105 or 150 volts, and the thyratron anode potential starts rising to its maximum of 300 volts. The voltage rise time is controlled by C_5 and R_{11} or R_{12}.

Since the Esterline-Angus recorder has a time scale, adjustment of R_{11} or R_{12} determines the voltage scale factor on the chart.

At completion of the cycle, when the thyratron conducts, C_8 transmits the negative pulse through RY_2 with sufficient amplitude to de-energize it and again apply the holding voltage to the thyratron. Without such a scheme the cycle would repeat itself. A simple modification to manual control would enable more than one plateau per tube to be obtained.

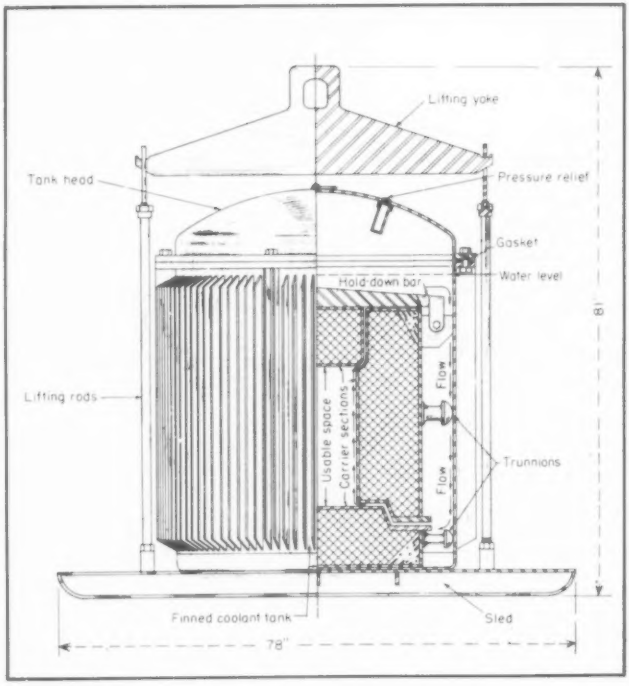
If RY_1 is opened by an increase of integrated output of the rate-meter circuit, RY_2 is de-energized which causes the high voltage to drop to a safe value to protect the G-M tube. The 1N34 diode prevents the charge on C_8 from discharging through RY_2 in such a manner that if RY_1 opened, thus opening RY_2, this remaining charge would cause RY_2 to close again after RY_1 closed.

The travel of the recorder paper is started at the time of closure of the contacts of RY_2. Speed-change gears on the recorder have been adjusted so that six major divisions of the chart pass in 22.5 sec.

In setting up the instrument, all adjustments are made with the G-M tube disconnected. Overload relay RY_1 is adjusted by means of a pulse generator applied to the input terminals, with the high voltage off, until RY_1 opens at some counting rate below that harmful to the G-M tube.

* * *

This work was done under Contract AT-04-1-GEN-12 with the U. S. Atomic Energy Commission.



Large Radioactive-Material Carriers

By J. J. WALLACE
Supervising Engineer, Engineering Department
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Large carriers such as the one pictured have recently been designed and built for Operations Division of the Oak Ridge National Laboratory. The interest in carriers of such size stems from the fact that the number of pounds of shielding material per cubic foot of usable volume decreases as the size of the carrier is increased. Heat dissipation, however, becomes a

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problem in large carriers since the surface area does not increase as rapidly as the volume.

The design shown here has a finned coolant tank containing water as the coolant. Cooling-water capacity and heat-radiation surfaces have been chosen to prevent boiling of the cooling water for the type and quantity of radioactive material to be transported in this carrier. Circulation of the water is induced by thermal convection. Loss of water by evaporation is prevented by the use of a gasketed tank head. This, however, requires the use of a pressure relief valve as a safety measure; location of the valve is shown in the illustration.

The carrier proper (which is removable from the coolant tank) is composed of three separable sections to facilitate decontamination. These sections are lead-filled stainless-steel shells. Insofar as practical, the places that would be difficult to decontaminate, such as sharp inside corners, cracks, threaded holes, etc., have been avoided.

Aside from cooling, total weight is the limiting factor to the size of such carriers, since they must be portable. The carrier, as shown here, weighs nearly six tons and therefore requires adequate means of handling and load distribution, such as is provided by the lifting yoke and sled. The carrier sections themselves are equipped with trunnions located near the center of gravity of each section for ease of both lifting and inverting.

Ruler for Drawing Radioactivity Decay Curves

By P. B. AITKEN
Chemistry Branch, Atomic Energy Project
National Research Council
Chalk River, Ontario, Canada

Many measurements of radioactivity involve drawing decay curves. Research chemists in this department have found that conventional types of French curves, ships curves, splines etc. are often inadequate for drawing decay curves—particularly that part of the tail of the curve that is almost but not quite straight.

To meet this need we have constructed a special "Decay Curve Ruler." This is a Lucite straight-edge 36 in. long by 5 in. wide. A sawcut is made 1 in. from one edge, from one end almost to the other, as shown in Fig. 1. By placing a suitable wedge in this cut the edge of the ruler is given a shape which varies from a straight line at the wedged end to a large radius curve at the other end, Fig. 2.

While it would be possible to produce many types of curve by making the sawcut curved or nonparallel to the edge, the cubic curve given by the parallel sawcut is generally satisfactory.

TECHNICAL BRIEFS

• **Control-rod gas seals,** used to prevent escape of gases from a reactor, are being studied by W. A. Heywood and C. J. Hibbert at Knolls Atomic Power Laboratory, Schenectady, N. Y. In KAPL-669, they report that lubricated O-ring seals most closely approach the design requirements of 10^{-3} cm³/min leakage with less than 10 lb friction drag at a reciprocating velocity of 10 ft/min. A combination grease and O-ring seal is being developed.

• **Tritium** is no more dangerous than other forms of radiation, according to research carried out by the Biological and Medical Research Division of Argonne National Laboratory, Chicago, Ill., under the direction of A. M. Brues.

• **Assumption** that alcohol is oxidized to acetaldehyde in the body has been proved by Drs. T. N. Burbridge and C. H. Hine of the University of California Medical Center. Radioactive carbon was used in tracer experiments aimed at studying the metabolic effects of alcohol.

• **Carbon** can be soldered directly to metal with a new process developed by Stackpole Carbon Co., St. Marys, Pa.

• **Watt-hour meter** is used as basis of instrument for finding rms value of a plotted curve. A tracing pen which follows the curve develops a voltage proportional to the position of the pen. This voltage and the corresponding current are fed into rotating-type watt-hour meter. Resultant registrations of the meter are proportional to effective value of trace. A second watt-hour meter reads only d-c value of the trace, so that rms value is determined. The device was developed by C. M. Crain and M. F. Hainey, Electrical Engineering Research Laboratory, University of Texas, Austin, Texas.

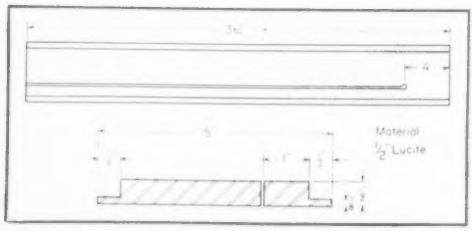

FIG. 1. Construction of decay-curve ruler

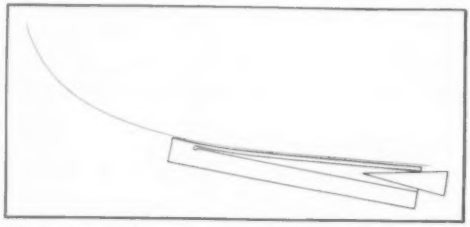

FIG. 2. Use of decay-curve ruler

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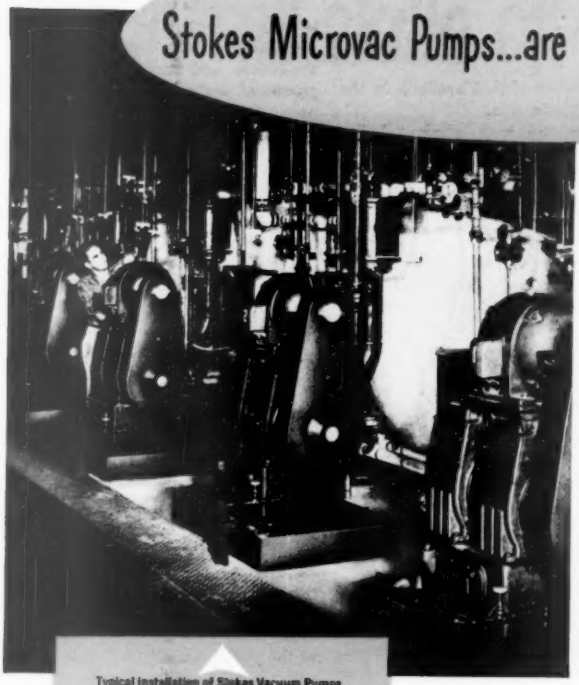

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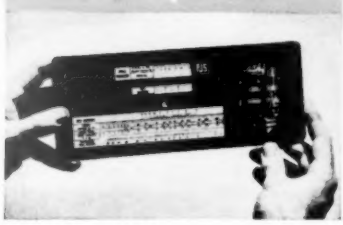

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BOOKS

Radioactivity Applied to Chemistry, edited by Arthur C. Wahl and Norman A. Bonner, John Wiley & Sons, Inc., New York, 1951, xv + 604 pages, $7.50.

Professors Wahl and Bonner and the able former graduate students who helped them at Washington University are to be congratulated for their joint effort in the bringing out of this first postwar book on applied radiochemistry. Their treatise has been written for the reader with a good knowledge of chemistry but with no more than an elementary grasp of radiochemistry.

The book should prove immensely useful as a text in graduate instruction. It should also prove to be perhaps even more valuable as a reference work, and, as such, it is strongly recommended.

The first 320 pages (Part I) reveal the very broad range of application of isotopes to chemistry. Chapters are devoted to isotopic exchange reactions; to radioactivity applied to kinetics, molecular structure, self-diffusion, analytical chemistry and surfaces; to behavior of carrier-free tracers; to discovery and properties of the synthetic elements; and to hot-atom chemistry and emanation methods. The reviews given of these subjects are models of clarity and comprehensiveness. They are pervaded by a critical spirit which doubtless is the residuum of a great deal of stimulating seminar discussion of the content and significance of the source literature covered.

The entirely different, but no less valuable, Part II comprehends, in eighteen extensive tables, much of the wealth of experimental data on the application of radioactivity to chemistry accumulated in the half century since Becquerel's epoch-making discovery.

In addition, there are six appendixes and an exhaustive bibliography of over 1,500 references extending up to 1950. These compendia, which are an indispensable key to the literature, may also be employed to supplement the discussions of Part I. Of course, they can never be a substitute for the primary sources. The editors are fully aware of this limitation, and they wisely caution the reader that the information in the tabular summaries is only representative and may be but a small fraction of that available in the original publication.

The success with which "Radioactivity Applied to Chemistry" attains its goal as a reference treatise is of no small dimension. There appear to be few, if any, errors of commission in the book.

The title has possibly led to the exclusion of some subjects of great interest to chemistry which might logically have been included. Radioactivity is not necessary for the study of isotopic exchange, reaction kinetics, molecular structure, self-diffusion, etc. In these cases it has frequently afforded a convenient analytical tool; however, stable isotopes may also serve. Possibly, therefore, a discussion of the application of stable isotopes to chemistry would have been of greater interest than a whole chapter given to the unimportant use of radioisotopes for surface-area determinations.

The aim to prepare an integrated book with uniform organization, terminology, and style was fully achieved, and the editors are to be praised. The typography is easy to read and pleasing to the eye. An excellent printing job has been done on the tables.

—G. E. Boyd
Associate Director, Chemistry Division
Oak Ridge National Laboratory

Quantum Theory of Matter, by John C. Slater, McGraw-Hill Book Co., Inc., New York, 1951, xiv + 527 pages, $7.50.

It is surprising how many subtleties in theoretical physics can be adequately described and discussed using little or no mathematical formalism.

In this respect, books by J. C. Slater are a most refreshing contrast with the present trend to stress the mathematical tool at the expense of the physical intuition and physical picture. Slater's books are characterized by fluent style, lucid presentation, and successful avoidance of excess mathematics. There are few, if any, physicists who combine a comparable record in the field of research in theoretical physics with prolific writing of excellent books. The present, "Quantum Theory of Matter," is the sixth book by Slater (three of them jointly with Frank) to appear in the International Series in Pure and Applied Physics.

As indicated in the preface, the book is written partly for chemists and metallurgists, who do not have the theoretical and mathematical background of professional physicists, and partly for those who are interested in various recent more advanced topics. Although there are only 500 and some pages, the book covers an enormous amount of basic information in the field of quantum theory of matter, which, in effect, is the cornerstone of our present outlook on the physical world (with the probable exception of nuclear physics).

The first chapter on de Broglie waves and wave mechanics deals briefly with these most fundamental aspects of modern physics and is followed by a discussion of the Schrödinger equation and of the WKB method treated in a necessarily descriptive manner. Next the matrix mechanics and the use of operators is introduced, followed by a chapter on perturbations and on Dirac's theory of the radiation field. The latter includes among others a section on the method of variation of constants.

These 100 or so pages of introduction to the basic principles and methods of quantum mechanics precede a comparable group of three chapters on atomic structure: One deals with the hydrogen atom, one with the central field model in general, and one with the multiplet structure. They cover such topics as the self-consistent field, degeneracies, Zeeman effect, the matrix components of energy, etc.

The molecular structure and, in particular, the Heitler-London method and its comparison with the method of molecular orbitals are discussed next. This is a particularly important preparation for a later analysis of the various approximations in the solid-state theory. The interatomic and intermolecular forces are dealt with in another chapter with a particular emphasis on the nature and properties of the covalent bond.

The rest of the book is devoted to the solid state, and here one appreciates the wise preparatory choice of topics in the earlier part. In the introductory chapter to this section of the book, the metallic state is discussed from the point of view of the covalent bond and from the band-theory point of view. This is followed by a survey of the basic ideas about mechanical, chemical, and thermal properties of matter, such

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as slip, dislocations, rates of reactions, etc. Electrical conductivity is then discussed, with paragraphs on Hall effect, semi-conductors, rectification, etc. A brief chapter is concerned with dielectrics, polarization, and Van der Waals forces. Finally, the last chapter is devoted solely to magnetism. It is indeed impressive how many aspects of this vast topic are treated in this short space. In the reviewer's opinion, the part of the book dealing with solid state is of particular value because it throws critical light on numerous important questions and introduces the reader to the "front line" concepts and problems of solid-state physics.

A very commendable feature is the addition of 22 appendixes which deal in greater detail with a number of specific topics such as the quantum theory of the electromagnetic field, group velocity, the WKB method, Hermitian matrixes, electronic theory of ferromagnetism, etc. The treatment here is, of course, more mathematical than in the main body of the book.

Another feature which may be of great value to readers consists of numerous problems appended to each chapter.

The great value of the book lies in a clear and rather nonmathematical introduction to the basic concepts and theories of quantum theory of matter. It will be much appreciated by all those who want to acquire a better understanding of the language and of the facts of theoretical physics without necessarily mastering its mathematical tools.

—R. SMOLUCHOWSKI
Department of Physics
Carnegie Institute of Technology
Pittsburgh, Pennsylvania

The Design and Analysis of Experiments, by Oscar Kempthorne, John Wiley & Sons, Inc., New York, 1952, xix + 631 pages, $8.50.

This book is the latest addition to the publisher's series on mathematical statistics. It was designed as a text for students at Iowa State College who have had previous training in statistical methods. Therefore, it is not an elementary introduction comparable with Youden's "Statistical Methods for Chemists." However, it is a valuable complement to such a book for scientists who wish to go more deeply into the mathematical bases for the standard designs used in their experimental work.

The introductory chapters show experimental design as a pattern for testing a particular hypothesis in an economical way and discuss the statistical approach as part of the scientific method. The theory of least squares and a treatment of linear hypothesis are then introduced as the elements of statistical design.

The majority of the book is devoted to a mathematical development of the most useful designs, based on least squares and linear hypothesis theory. Emphasis is placed on estimating the magnitude of treatment effects as well as determining the likelihood of their existence.

The designs treated include randomized blocks, latin squares, factorials, split plots, lattices and incomplete blocks. They are considered particularly in the terms of efficiency and sensitivity to variation due to treatment effects. As in the development of the designs, the comparisons are in symbolic terms, with very few numerical examples.

The nonstatistician will have difficulty with some of the terminology and symbols, which are not defined. In compensation, many of the fundamental concepts, such as randomization are explained with exceptional clarity.

Tables of variance ratios used in tests of significance and of functions useful in evaluating the sensitivity of a design are given in the appendix.

The author has apparently fulfilled his purpose of writing a text for advanced students in the field of statistics. For other scientists, a good grounding in elementary statistical theory will be necessary before they can make full use of the book.

—JOHN H. HARLEY
Chief, Analytical Branch
Health and Safety Division
New York Operations Office
U. S. Atomic Energy Commission

BOOKS RECEIVED

Experimental Nucleonics, by Ernst Bleuler and George J. Goldsmith, Rinehart & Company, Inc., New York, 1952, xv + 393 pages, $6.50. *(To be reviewed.)*

Miscellaneous Physical and Chemical Techniques of the Los Alamos Project (Experimental Techniques) (Div. V, Vol. 3, of National Nuclear Energy Series), edited by Alvin C. Graves and Darol K. Froman, McGraw-Hill Book Company, Inc., New York, 1952, xiii + 323 pages, $4. *(To be reviewed.)*

Elements of Wave Mechanics, by N. F. Mott, Cambridge University Press, New York, 1952, ix + 156 pages, $3.75. *(To be reviewed.)*

Principles of Geochemistry, by Brian Mason, John Wiley & Sons, Inc., New York, 1952, ix + 276 pages, $5. *(To be reviewed.)*

Water (A Study of Its Properties, Its Constitution, Its Circulation on the Earth, and Its Utilization by Man), by Sir Cyril S. Fox, Philosophical Library, New York, 1952, xxvii + 148 pages, 20 photographs, $8.75. The author, well known for his geological survey work in India, touches on many of the academic, economic, engineering, and practical aspects of water supply in this comprehensive and interesting treatise. He discusses heavy water and radioactive water at Bikini and elsewhere briefly.

A History of the Theories of Aether and Electricity, by Sir Edmund Whittaker, F.R.S., Philosophical Library, New York, 1951, xiv + 434 pages, $12.

This book deals with classical theories. It is the first of two volumes planned by the author as a complete rewrite of his earlier book on the subject published in 1910. The chapters are well documented. Among new material added in this volume is the origin of the relativity and quantum theories and notes on their development since 1900.

Elements of Thermodynamics and Statistical Mechanics, by E. O. Hercus, Melbourne University Press (Cambridge University Press), New York, 1950, ix + 153 pages, $3.75. For physics majors with a moderate knowledge of mathematics who are interested in historical background of the title subjects.

The Rise of the New Physics (Its Mathematical and Physical Theories) (2d edition), by A. D'Abro, Dover Publications, Inc., New York, 1951, ix + 982 pages, in 2 volumes, $8 per set. The first edition of this treatise was put out in 1939 under the title of "Decline of Mechanism" and was published by D. Van Nostrand Co., Inc. The Dover edition has been

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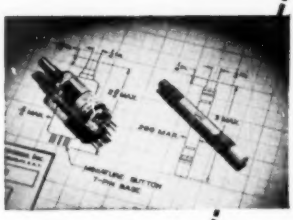

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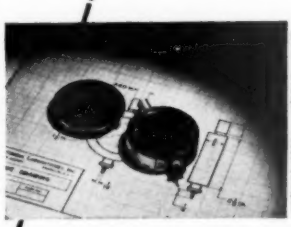

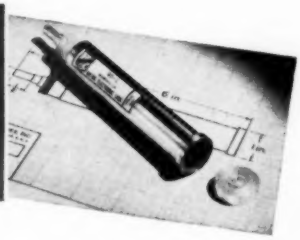

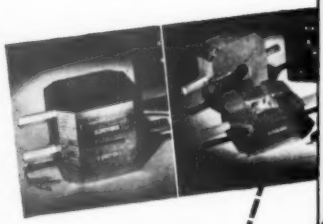

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corrected and enlarged with the addition of 36 full-page portraits of renowned scientists. In it the author, with a minimum of mathematical discussion, attempts to draw a sketch of classical mathematical physics and the rise of the quantum theories.

OTHER LITERATURE

Laboratory Design for Handling Radioactive Materials. Laboratory layout and construction, shielding, surfaces and finishes, air supply and exhaust, and waste disposal are discussed in this 140-page, illustrated report, which also contains a bibliography and glossary of nuclear terms. It comprises the proceedings of a conference on the subject held in Washington, D. C. in November, 1951, sponsored by the American Institute of Architects and the Atomic Energy Commission. *Building Research Advisory Board, National Research Council, 2101 Constitution Ave., Washington 25, D. C., $4.50.*

Chemistry and Physics of Radiation Dosimetry (Part 1, Unclassified Papers). In September, 1950, the Technical Command, Army Chemical Center, Maryland, conducted a symposium on this subject, and the major portion of this 180-page report is devoted to nine unclassified papers presented at it, which have only now been released by the Department of Defense and the Atomic Energy Commission. Titles of the papers are: Review of the chemical effects of ionizing radiation; Mechanism of radiation chemical reactions in organic and in aquo-organic systems; Solvent activated radiation reactions in aqueous solutions; Theory of radiation chemistry (some chemical effects of variation of ionization density); Crystal chemistry of defective structures with respect to radiation; Luminescent solids (phosphors); Effect of radiation on colloidal and high polymeric substances; Thermoluminescence and related properties of crystals; and The UCLA dosimeter, its recent modifications and additional applications. *Item PB-105,925, Office of Technical Services, Dept. of Commerce, Washington 25, D. C., $4.75.*

Isotopes—A Five-Year Summary of U. S. Distribution (U. S. Atomic Energy Commission, August, 1951,

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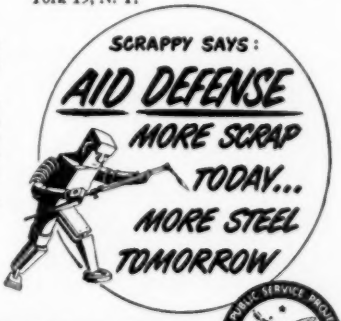

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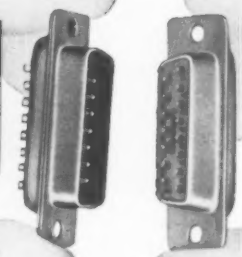

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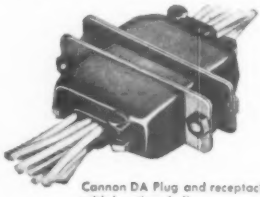
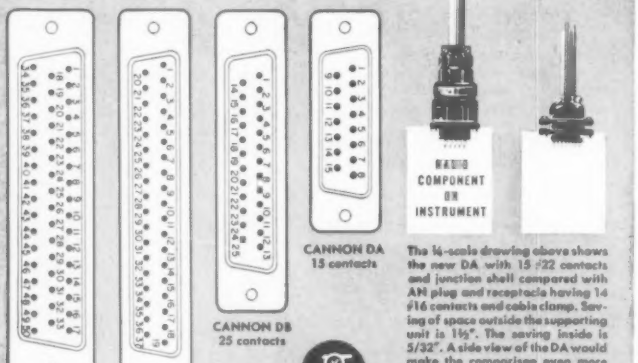


Cannon DA Plug and receptacle with junction shells.



The 14-cents drawing above shows the new DA with 15 #22 contacts and junction shell compared with AN plug and receptacle having 14 #16 contacts and cable clamp. Saving of space outside the supporting unit is 1½". The saving inside is 5/32". A side view of the DA would make the comparison even more startling.

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451 pages). This detailed account of isotope utilization during the first five years of the AEC's distribution program shows that 18,905 shipments of radioactive and 1,535 shipments of stable isotopes were made to domestic users and that 1,135 shipments of radioactive isotopes went to foreign users during that time. Discussions of the growth of the isotope program and its future are included. The most interesting section of the report is given in an appendix. It is a tabulation, occupying 335 pages, showing almost all the institutions receiving isotopes, names of the investigators, the project for which used, and its status. A bibliography lists the titles of 1,402 technical reports and papers published on isotope work in the two years following the AEC's three-year summary report. Both as a reference and documentary evidence of the value of radioactive and concentrated stable isotopes in industry, science, medicine, and agriculture, the report will be useful to anyone using or contemplating the use of isotopes.* *GPO, Washington 25, D. C., $1.*

Protecting Personnel in Wartime (Studies in Business Policy No. 55, 1952, 122 pages, $4). Prepared by the National Industrial Conference Board, this report is "must" reading for civil-defense planners in both industry and community. Data were gathered at first hand from managers of British, German, and other European companies who directed their firms' operations during WW-II bombings. Floor plans and pictures of different types of shelters illustrate the report, together with the technical details of their construction and the protection offered. The report also contains many tabulations on work plans, methods of saving production time, shelter protection during A-bombings in Japan, medical and first-aid services, etc. It is a companion study to the NICB report entitled **Damage Control in Wartime** (Studies in Business Policy No. 53, 1951, 80 pages, $3) in which protective measures against blast, fire, ground shock, and splinters, are suggested for industry. Another NICB study is

* A summary of isotope applications of particular interest to industry has been compiled from the Five-Year Summary and has been printed separately under the title "Radioisotope Applications of Industrial Significance." It is available as document TID-5078 from the Office of Technical Services, Dept. of Commerce, Washington 25, D. C., at $0.30 per copy.

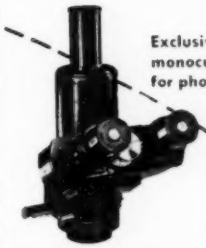
entitled **Executive Planning if an A-Bomb Falls** (Studies in Personnel Policy No. 108, 1950, 20 pages, $1). *National Industrial Conference Board, Inc., 247 Park Ave., New York 17, N. Y.*

Atomic Energy and Private Investment (April, 1952). This is a broker's leaflet containing a well-written, up-to-date statement on the atomic-energy program and some of its vast facets. It observes that whether the program "will present opportunities for giant American corporations to become bigger or whether it will add the spark to make obscure companies great remains to be seen." Many of the companies affected by the program's current expansion are named. *Free on request from Hirsch & Co., 25 Broad St., New York 4, N. Y.*

Atomic Energy Progress: A Critical Review and Appraisal, 1942–1951. The 30-page proceedings of a seminar sponsored by the Religious and Welfare Committee of the New York Committee on Atomic Information, Inc. Texts of these talks are included: *Highlights of Domestic Progress in Atomic Energy*, by Morse Salisbury, Atomic Energy Commission; *Progress in Reactor Development*, by George L. Weil, Atomic Energy Commission; *Progress in Biology and Medicine*, by Edward Roll, Memorial Center for Cancer and Allied Diseases, New York; *Progress in International Control of Atomic Energy*, by Peter Kihss, UN Bureau, "New York Herald Tribune"; and *Historical Significance of Basic Research in Atomic Energy*, by Karl Hartzell, Associated Universities, Inc. *New York Committee on Atomic Information, Inc., 39 Broadway, New York 6, N. Y., $1.*

BOOK NEWS

• **"Engineering Index" reprint.** The 1928–1949 volumes of "The Engineering Index," no longer available in the original edition, have been reprinted by Johnson Reprint Corporation, 125 E. 23d St., New York 10, N. Y. Internationally known as a record of developments in the various fields of engineering, they include transactions of engineering and allied societies, miscellaneous articles and reports, and reviews of scientific and technical books. All cloth-bound, the 1928–1932 volumes are $300 per set or $70 for a single volume; 1933–1949 are $900 per set or $60 for a single volume.



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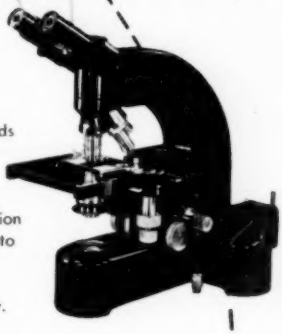

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NUCLEONIC EVENTS

Five Universities May Build Low-Power Research Reactors; AEC to Announce Policy Shortly

At least five major universities have expressed interest in following the steps of North Carolina State College (NU, Dec. '50, p. 5) by building research reactors outside of Atomic Energy Commission sites. Proposals —several firm ones and several of the "feeler" variety—have gone to the AEC from these schools, according to authoritative sources.

Action by the AEC is awaiting formulation of a broad policy to cover these and future proposals. It is expected that an announcement on this will be made some time this month. According to the McMahon Act, the AEC is "directed to distribute sufficient fissionable material to permit the conduct of widespread independent research and development activity, to the maximum extent practicable."

The principal questions which AEC must find answers for are:

1. Shall AEC give financial support to an institution wishing to build a reactor where that institution cannot foot the whole bill?
2. Where a school wants to pay for the whole project with its own funds (such as North Carolina State College is already doing), can AEC say "no"?
3. Regardless of financial factors involved, what limitation does the quantity of fissionable material available place on the number of non-AEC research reactors which can be built?
4. From the health and safety point of view, what types of reactors should AEC permit universities to build?

Wrapped up in AEC's answer to question 1 are the "strings" which might be attached to any arrangement where AEC shares part of the cost. In the absence of an over-all Government policy on the method to be followed in supporting the construction and operation of costly research facilities on college campuses, it would appear that prudent management of AEC funds would require that some portion of the research potential of such a facility be available for work of direct interest to the academic institutions interested in the acquisition of research reactors.

At least one of the five schools is anxious to build a water boiler with its own funds. It hopes to do this for about $50,000—the least any such nuclear reactor has been built for.

Another school has been studying the "solid-type" homogeneous reactor designed by North American Aviation (NU, Jan. '52, p. 71).

The regents of one university have just approved spending nearly $1/2$-million for a building to house a reactor and for laboratory facilities.

The Oak Ridge mock-up of the Idaho Materials Testing Reactor (described on pp. 75–76 of this issue) is being considered by another one of the universities.

Another possibility for a research reactor is the "swimming pool" at Oak Ridge (also described, pp. 75–76).

Involved in the decision of a university on the type of reactor it might build are such questions as:

1. Does the school want a ready-made design or does it want to develop its own design?
2. Does the site available impose any limitations from the safety point of view on the type of reactor selected?
3. What range of operating characteristics are required to meet the research and educational objectives?
4. What flexibility of reactor configuration is desired for educational purposes?

Belgian Scientists to Study Reactor Technology During Three-Month Stay at Argonne

Eleven Belgian scientists and engineers have arrived at Argonne National Laboratory for the purpose of intensive study of unclassified reactor technology. Arrangements for the three-month visit were made last year by representatives of the United States and Belgium, whose African Belgian Congo colony is the world's largest producer of uranium.

It is reported that plans are under way for the Belgians to build a nuclear reactor similar to Argonne's CP-2, which is located at Palos Park in Chicago, Ill. The latter is a 200-watt natural-uranium, graphite-moderated reactor that was declassified in November, 1950 (NU, Dec. '50, p. 76). The Belgians will have access to the CP-2 reactor during their stay and will probably use it to carry out experiments.

The information being made available to these scientists, which presumably should be available to any similarly interested American group, will include unclassified or declassified material on design, development, construction, and operation of reactors.

Before coming to Chicago, the group had been briefed in Brussels in a series of lectures on unclassified reactor technology conducted by British nuclear scientists. At the end of their Argonne stay, the Belgians will make brief visits to Oak Ridge National Laboratory, Oak Ridge, Tenn., and to Brookhaven National Laboratory, Upton, N. Y.

AEC Offers Fellowships in Industrial Hygiene

Up to four fellowships in industrial hygiene are being made available by the Atomic Energy Commission, which recently announced its inauguration of this training program for the purpose of encouraging chemists and engineers to equip themselves for work in this field. The program, starting this fall, will be administered by the Atomic Energy Project of the University of Rochester.

Applicants, to qualify, must have a degree in engineering (preferably chemical), chemistry, or physics. As stipend, the industrial hygiene fellow will receive $1,500 per annum if single or $2,000 if married (with an extra allowance for children). Graduate work

in a related field will make the candidate eligible for $200 additional. No commitment will be asked of the candidate to accept employment with the AEC.

Application blanks may be secured from Mr. Merril Eisenbud, New York Operations Office, U. S. Atomic Energy Commission, P. O. Box 30, Ansonia Station, New York 23, N. Y.

European Nations Push Nuclear Lab Plans

Nuclear scientists from the United States and Europe have been invited to a conference in Copenhagen from June 3-21 for the purpose of determining nuclear research problems that could be handled by European cooperation and the type of instruments needed in a laboratory which eleven European nations will pool their funds to build (NU, Sept. '51, p. 80-82).

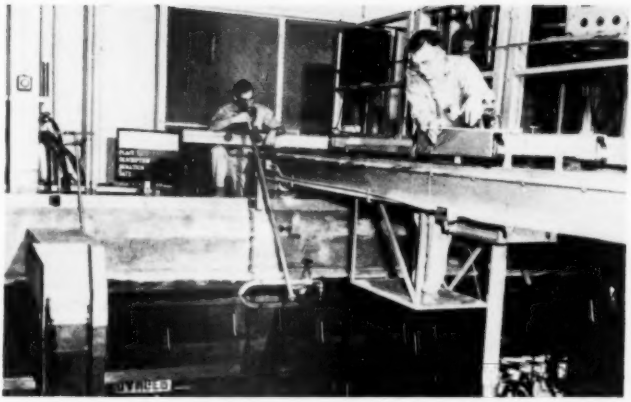
Niels Bohr of Denmark and Werner Heisenberg of Germany have organized the conference which grew out of a meeting in Paris last month during which additional plans for the project were revealed by representatives of the eleven countries. Five of the nations have ratified an agreement for setting up a fund of $200,000 to finance a year or more of preliminary planning toward eventual establishment of facilities for fundamental nuclear physics research at least as great as those offered in this country.

According to the latest information, the group hopes to build, in additional to the laboratory, a 550-Mev synchrocyclotron and a 10-Bev cosmotron.

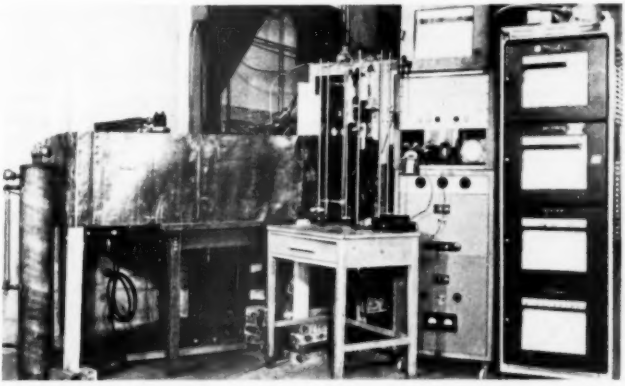
A Council, with E. Amaldi of Italy as secretary, has been organized to administer the work first sparked by the United Nations Educational, Scientific, and Cultural Organization.

The study group investigating construction of the synchrocyclotron is headed by C. J. Bakker of The Netherlands, and O. Dahl of Norway is leader of the group to consider building the cosmotron. Niels Bohr is chairman of the theoretical studies group, and L. Kowarski of France will direct the work of those studying the organization of an international laboratory.

The eleven countries represented on the Council are Belgium, Denmark, France, Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, and Yugoslavia.



"SWIMMING POOL" REACTOR at Oak Ridge is part of bulk shield testing facility. This low-cost, low-power reactor is set up for operation under water of pool. One operator is seen above locating an instrument to measure neutron flux about 15 feet below surface while another observes the test by telescope (see story below)



LOW-INTENSITY TEST REACTOR at Oak Ridge has horizontal beam holes where samples of reactor construction materials can be tested under neutron bombardment. Here equipment used in connection with tests is shown surrounding a beam hole, concealed by the lead shielding at the left (see story below)

AEC Lifts Curtain on "Swimming Pool" Reactor and Mock-up of Materials Testing Reactor at Oak Ridge

Details of two nuclear reactors, which went into operation at the Oak Ridge National Laboratory during the past two years, were released recently by the Atomic Energy Commission and the Carbide and Carbon Chemicals Company, which operates ORNL for the Commission. One is a unique, relatively inexpensive, low-power reactor that is submerged in water which acts as a radiation shield. The other is the low-intensity test reactor (LITR) which served as the mock-up for the Arco, Idaho, materials testing reactor (MTR) and has since been improved to operate at a higher power to provide an additional research facility at the Oak Ridge laboratory.

Both the "swimming pool" reactor, as the former is popularly known, and the LITR use fuel elements that had been designed for the MTR. Because of the advanced design of the LITR, its core structure and fuel arrangement remain classified, but it is known that

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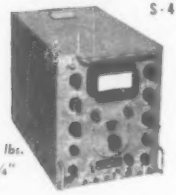

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ordinary water is used as a coolant and uranium enriched in U^{235} as fuel.

The swimming pool reactor was constructed for a little more than $200,000, exclusive of fuel, while the LITR cost about $1,000,000. Of the $200,000 for the pile pool, $58,400 went for the reactor core structure itself, the rest being used to pay for concrete work, the building, and auxiliary equipment. It has a continuous, full-load power rating of 10 kw at which it produces a neutron flux of 10^{11} n/cm²/sec.

"Pool" for Shielding Tests

The central feature of a bulk shield testing facility, the pool pile is used for experiments to aid development of improved reactor shields. It is submerged in a 130,000-gallon pool of water 20 ft deep, 20 ft wide, and 40 ft long, in which it can be moved about. On December 17, 1950, it went critical and was put in operation soon after.

The reactor is an assembly of movable fuel elements placed on end in an aluminum grid. It is suspended by an aluminum framework from a bridge that spans the pool. This reactor bridge rests on wheels fitted to rails along either side of the pool, so that the reactor can be moved along a center line the length of the pool.

Similarly, an instrument bridge as seen in the photograph on page 75 spans the pool and operates on the rails. A steel framework attached to the movable mechanism of this bridge extends nearly to the bottom of the pool. Using a carriage that slides up and down on the framework, operators can place test instruments at any point in the pool.

A useful feature of the facility is an aluminum gate, 12 ft high and 21 ft long, 10 ft from one end of the pool. When the reactor is moved to this end of the pool, the gate can be lowered and the greater area of the pool can be blocked off and pumped dry. Thus, some repairs and adjustments are facilitated, and instruments and shielding samples can be easily placed in desired spots, with personnel meanwhile protected from radiation.

Shielding measurements on samples can be made also in the open air, with samples placed near the dry side of the gate and the reactor moved close to the other side of the gate.

Centered on the bottom surface of the pool is a well, 14 ft square and 5 ft deep. This well is filled with removable blocks of high-density concrete, giving part of the pool an adjustable floor level for more flexibility in placing shielding samples and instruments.

The reactor has a variety of potential uses in addition to its principal role as an aid in the testing of shields. It enables students and other investigators to perform critical experiments, study neutron distribution, and, within limits, study the effects on reactor operation of various patterns of arrangement of the fuel elements.

LITR Used for Research

ORNL's low-intensity test reactor can produce both fast and slow neutrons at varying intensities. It has a high neutron density and is being used to make high-priority tests of radiation effects on certain construction materials of possible use in future reactors (see photograph). Limited quantities of rare isotopes, such as chromium-51, will also be produced in it.

The reactor itself is about two and a half stories high, with a cylindrical tank enclosing the reactor core.

LITR went critical early in the spring of 1950 as a mechanical model of the working parts of the materials testing reactor, now in operation at the AEC's National Reactor Testing Station in Idaho (NU, May '52, p. 74). When the model had proved the design and engineering aspects of the MTR, small amounts of nuclear fuels, control devices, shielding, and instruments were added.

The result was a low-thermal-energy reactor that was used to test the nuclear characteristics and performance expected in the Idaho reactor.

Later, when more nuclear fuel and shielding were added, the Oak Ridge pilot model was used to train operators for its bigger counterpart, the MTR.

Limited research facilities were then provided, consisting primarily of added rooms and equipment on two sides of the temporary structure which houses the reactor. The reactor "building" is really only a mixture of concrete, concrete block, metal sheathing, plain wood siding, and even tarpaper covering; it is not intended as a permanent facility.

Murray Confirmed for New 5-Year Term on AEC

Thomas E. Murray, who was named to the Atomic Energy Commission early in 1950, has received Senate confirmation for a new five-year term. Cited as "an outstanding example of a

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successful and prominent public official, humbly devoted to his faith," Mr. Murray last month received from Francis Cardinal Spellman the 1952 Laetare Medal, an award made annually to a Catholic who has performed a public service with the greatest distinction.

Shields Warren Leaves AEC Post, Bugher Succeeds Him

The resignation of Dr. Shields Warren as director of the Division of Biology and Medicine of the Atomic Energy Commission has been accepted with regret by the AEC and will become effective June 30. At that time he will become a member of the Commission's Advisory Committee for Biology and Medicine, and Dr. John C. Bugher will succeed him in the former post. Dr. Bugher, pathologist and bacteriologist, has served the AEC as deputy director of Dr. Warren's division since February, 1951.

In his letter of resignation, Dr. Warren cited accomplishments of the Division, which is now in its fifth year, and indicated that stress of the work and the strain of "tens of thousands of miles of travel yearly," which "are making themselves felt," were behind his decision to resign.

In accepting Dr. Warren's resignation, M. W. Boyer, AEC General Manager, warmly praised Dr. Warren's "common sense development of biological and medical studies" and said that "every part" of the atomic energy program had been advanced by the confidence springing from his accomplishments.

Dr. Warren, after June 30, will resume his duties as full-time pathologist at the New England Deaconess Hospital in Boston, which work was curtailed during his service with AEC.

International Conference on β, γ Radiation Planned

An International Conference on Beta and Gamma Radioactivity is to be held in Amsterdam from September 1–6, under the sponsorship of The Netherlands Physical Society, supported by the International Union of Pure and Applied Physics. It is expected that many nuclear scientists from the United States will attend.

The program, as tentatively scheduled, includes papers by C. S. Wu (*Beta disintegration, allowed and for-*

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2. Presents a variety of the physical and chemical laboratory methods used in the early days of atomic research. Deals with techniques of foil preparation, methods of preparing neutron sources, etc. Discusses apparatus used, such as the modulated betatron, diffusion pumps, vacuum valves, etc., **Div. V, Vol. 3, National Nuclear Energy Series. Edited by A. C. Graves, Los Alamos Scientific Lab., and D. K. Froman, both of Los Alamos Scientific Lab., 326 pp., 87 illus., $4.00**

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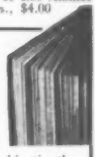

3. A thorough reference on atomic and nuclear fundamentals in the simplest possible terms. Covers high-voltage particle accelerators, the kinetic theory of gases, charge and mass of electron, electronics, photoelectric effects, X-rays, the Bohr theory of the origin of spectral lines, electron configuration in atoms. Treats matter waves, isotopes, and other important factors. **By Saul Dushman, Research Consultant, Gen. Elec. Co., Schenectady. 294 pages, 68 illus., $5.50**

ENERGY SOURCES

The Wealth of the World

4. A thorough census of our energy sources —past, present, and future. Reviews the size of fuel supplies, technology of production efficiency, conversion, and progress in conservation. Shows how man has used energy in the past and what use he may expect in the future. Everything from fossil fuels and hydroelectric power generations to nuclear and solar energy is discussed. **By Eugene Ayres, Gulf Research & Development Co., and Charles A. Scarlott, Editor, Westinghouse Engineer, 344 pp., 114 illus., $5.00**

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The secretary of the conference is Prof. Dr. J. de Boer, Bunsenstraat 98, Amsterdam-O, The Netherlands.

Radioactive Cortisone to Be Made for Research

The National Institute of Arthritis and Metabolic Diseases has made a fund of $66,000 available to manufacture radioactive cortisone for use in studying diseases involving the adrenal gland hormones.

When available, the product will be distributed to qualified scientists who submit formal research proposals to the Institute. Located in Bethesda, Md., the Institute operates under the supervision of the Public Health Service of the Federal Security Agency.

A small committee of scientists from nonfederal research institutions is presently at work at the task of administering the fund. Headed by Dr. Charles Huggins of the University of Chicago, this group is responsible for planning the project and contracting with a manufacturer to produce the drug.

Forrestal Research Center Dedicated at Princeton

Formal dedication of the James Forrestal Research Center at Princeton University, Princeton, N. J., took place last month, and plans for the work to be done there were revealed at that time.

To be used "for the advancement of science and engineering and the high-level training of workers in these fields," the Center already has basic research initiated in the fields of fluid mechanics, combustion, chemical kinetics, advanced thermodynamics, and

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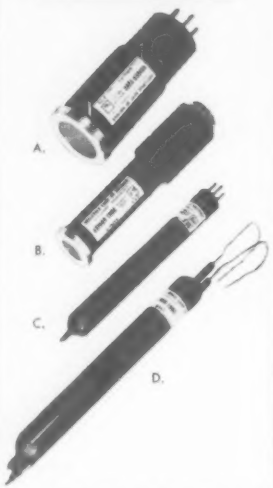

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applied mathematical analysis. It is adding to this program research in the solid-state sciences and has made plans to include a program in the nuclear sciences with the assistance of such Princeton physicists as Lyman Spitzer, John Wheeler, Milton White, and Eugene Wigner.

The buildings at the Center, which is on an 800-acre tract that adjoins the university property, were originally built and used by the Rockefeller Institute for Medical Research.

March Isotope Shipments Set New Record

The number of shipments of radioisotopes from Oak Ridge National Laboratory during March topped all previous shipment records. In all, 1,011 shipments were made, with iodine-131 and phosphorus-32 accounting for 56.3% of the total. Customers in foreign countries received 16 of the shipments, AEC installations 136, and hospitals, universities, and private industry the remaining 859.

The radioisotopes that were chemically processed comprised a little over three quarters of the shipments, while the pile units, that is, the unprocessed type, accounted for the remaining quarter.

New packaging methods and more convenient handling procedures are contributing both to the ease with which ORNL is turning out isotope shipments and to a reduction in shipping costs. Heavy, expensive, returnable containers were formerly used for almost all isotope shipments. Now about 30% of the isotopes made available are shipped in light, inexpensive containers that can be disposed of by the customer. In the case of phosphorus-32, the new container, weighs 2 pounds; the old-type returnable container weighed 9–15 pounds.

IN BRIEF

• **Keel laying.** The Electric Boat Company is scheduled to lay the keel of the Navy's first nuclear-powered submarine this month. The ship is being built at the company's yards in Groton, Conn., and should be completed in two years.

• **Ore treatment plant.** The Kennecott Copper Corporation is planning to build a large plant for uranium and copper ore treatment at Rum Jungle,

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vast but relativey undeveloped Australian uranium field. Australia wants preliminary treatment work done at Rum Jungle to reduce transportation costs. The American company would separate the uranium ore by flotation before treating the copper.

• **Chalk River news.** *Excavation and foundation work is well under way on the new $30,000,000 reactor at Chalk River, Ontario. Employees at the Canadian atomic-energy project now number well over 1,300.*

• **Giant skyhook.** What is expected to be the world's largest unmanned balloon will be launched this summer in the interests of cosmic-ray research. Named the U. S. Navy's "Giant Skyhook," it is a project of the nuclear physics branch of the Office of Naval Research.

• **Isotopes in Denmark.** *The Rockefeller Foundation has made a $32,000 grant to the University of Copenhagen for research in biology using radioisotopes.*

• **AEC patents.** *The Commission now has a total of 419 patents and patent applications that it will release to industry for licensing. Through its General Counsel, the AEC grants nonexclusive, royalty-free licenses on these patents, which cover a wide range of instruments and processes developed in AEC laboratories.*

• **Goldsmith award.** The first Hyman Goldsmith Memorial Award was given to Dr. Walter Gellhorn for his book "Security, Loyalty, and Science." Dr. Gellhorn, professor of law at Columbia University, received the $200 award from *The Bulletin of Atomic Scientists* for his contribution "to the clarification of the right relations between science and politics." To be given annually, this memorial was established to honor Dr. Goldsmith, a founder of the *Bulletin*. A brilliant technical information specialist, Dr. Goldsmith, at the time of his death in 1949, was head of the Information Division of Brookhaven National Laboratory and had served on NUCLEONICS' first editorial board.

• **Test house for sub plant.** *Last month the AEC awarded a $2,146,000 contract for the construction of the bell-shape building where the General Electric Co. will test the prototype of a submarine nuclear-power plant that it will build for the Commission (NU, Apr. '52, p. 74). The contract went to the Chicago Bridge and Iron Company which will start*

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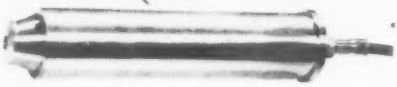

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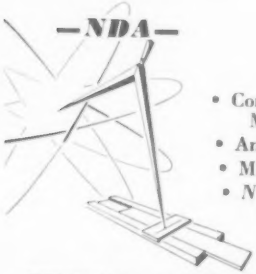

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construction at the building site in West Milton, N. Y., next month. The building, unique in design, will consist of a steel sphere, 225 feet in diameter.

• **Ear-marked funds.** $100-million has been set aside by the government for further expansion of the AEC's Hanford Works, Richland, Wash.

NUCLEAR NEWSMAKERS

Lindsley H. Noble last month resigned as controller of the Atomic Energy Commission to become comptroller of the Panama Canal Company. **Francis J. McCarthy,** AEC's assistant controller for budgets, was designated acting controller to replace Mr. Noble who joined the commission in 1947.

Lester W. Strock, who has served as private consultant and geochemical analyst for the Manhattan Project and the beryllium industries, is joining the staff of the physics laboratory of Sylvania Electric Products, Inc., Bayside, N. Y.

Logan B. Emlet, executive director of Oak Ridge National Laboratory since 1950, has been appointed superintendent of the Y-12 plant at Oak Ridge. He replaces **W. D. Lavers,** who resigned to take a position with another company.

William C. Moloney, blood specialist, has been appointed to the Atomic Bomb Casualty Commission in Japan. Dr. Moloney will direct research on the lingering effects of radiation.

George E. Boyd, associate director of the chemistry division of Oak Ridge National Laboratory, has received a Guggenheim Fellowship for a year's study abroad. He plans to investigate the physical chemistry of ion exchangers. Dr. Boyd received an additional honor recently with an invitation from the University of Notre Dame to give the Peter C. Reilly Lectures, an annual series of two- to four-week chemistry lectures which are later published by the Notre Dame press.

Samuel Colville Lind, of the Oak Ridge National Laboratory, was named recently as the recipient of the 1952 Priestley Medal, highest award of the American Chemical Society. Dr. Lind, a former ACS president and dean emeritus of the University of Minnesota Institute of Technology, is well known for his research on radium and

other radioactive substances and was cited for his "distinguished service to chemistry." The award will be presented at the ACS Fall Meeting in Atlantic City, N. J.

Harry Davis Bruner, chief scientist of the medical division of Oak Ridge Institute of Nuclear Studies, has been appointed chairman of the department of physiology at Emory University. He will take over the post on July 1.

Bernard E. Proctor, long associated with research in food technology as director of the Samuel Cate Prescott Laboratories of Food Technology at Massachusetts Institute of Technology, has been appointed head of MIT's Department of Food Technology.

Lloyd J. Roth, on the staff of the Los Alamos Scientific Laboratory in New Mexico since 1944, has been appointed assistant professor of pharmacology at the University of Chicago.

Sir George Thomson, who in 1940 headed up the famous committee of British scientists to determine the feasibility of producing an atomic bomb, has been named to succeed **Sir Will Spens** as Master of Corpus Christi College at the University of Cambridge. He has been head of the department of physics at the Imperial College of Science and Technology, London, since 1930.

Jules Halpern, department of physics, University of Pennsylvania, has been elected chairman of the Federation of American Scientists for 1952-53. The new vice chairman is **Victor F. Weisskopf,** department of physics, Massachusetts Institute of Technology. **Charles D. Coryell,** MIT department of chemistry, will serve as secretary-treasurer. Three physicists have been named to the executive committee. They are **David R. Inglis** of Argonne National Laboratory, **W. A. Higinbotham** of Brookhaven National Laboratory, and **A. H. Shapley** of the National Bureau of Standards.

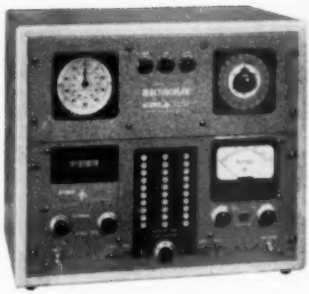
MEETINGS

Nuclear Chemistry Section of Gordon Research Conferences—New Hampton School, New Hampton, N. H., June 23-27

Atomic Energy Conference on Industrial and Legal Problems—University of Michigan, Ann Arbor, Mich., June 26-28

American Physical Society—Denver, Colo., June 30-July 3

Conference on Atomic Energy for Educators—University of Idaho, Moscow, Idaho, July 10-11



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CANADIAN MARCONI CO. Montreal, Canada

HAROLD A. KITTLESON CO. 7616 Melrose Ave. Los Angeles 46, Calif.

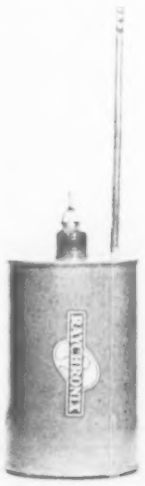
PRODUCTS AND MATERIALS

Proportional Counter Converter

Nuclear Measurements Corp., 3339 Central Ave., Indianapolis 5, Ind. The model PCC-12 converts any scaler with a high voltage range of 800–2,000 volts to a proportional counter. The counter is windowless and discriminates between alphas and betas by high voltage setting. Included in the unit are a gas-flow control, illuminated leakproof bubbler, amplifier, and pulse-height selector. All chamber parts are interchangeable and special chamber types may be used. Decontamination is claimed to take less than 20 min; maximum sample size is $8\frac{1}{2}$ in. diameter and 1 in. thick. Alpha and beta backgrounds are 0.5 and 240 cpm; resolution loss is 1% per 100,000 cpm. Plateau is 200 volts with a slope of 3% for the best 100 volts. The counter geometry is 2π for alpha and beta particles. The power requirements are 300 volts, d-c, at 20 ma, regulated 150 volts, d-c, at 6 ma, and 6.3 volts, a-c, at 1.4 amperes.

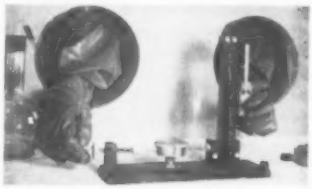
Portable pH Meter

Beckman Instruments, Inc., South Pasadena 37, Calif. The model N *p*H meter has ranges 0–8 and 6–14 *p*H with accuracy to 0.05 *p*H, and has built-in temperature compensation for full range, 0° to 100° C. A "check pointer" eliminates frequent buffer standardizations; plug-in electrodes are interchangeable. The meter can be used to measure voltages from −420 to +420 mv by using a metallic electrode in combination with the reference electrode. Condition of batteries can be checked at panel; the instrument is splash-proof and fully desiccated internally. The meter is supplied with glass electrode and fiber-type reference electrode, buffer, and KCl solution.



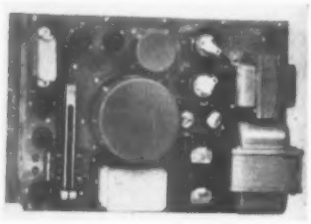
Fast-Neutron Counter

Radioactive Products, Inc., 443 W. Congress St., Detroit 26, Mich. The model F-1 recoil-type counter has a response proportional to the neutron sensitivity of human tissue over a range of 0.2–10 Mev. It has a methane-argon-filled chamber, high- and low-energy polyethylene radiators, and a 50-mg/cm² aluminum beta absorber. It is intended for operation with an amplifier having pulse-height discrimination to ignore the small gamma-ray pulses. Operating potential is 1,400 volts. Gamma radiation pulses are approximately 75 mv, maximum; neutron-induced pulses are up to 750 mv. Axial versus lateral radiation response is directional to the extent of 2:1. Over-all dimensions are 2 in. diameter and $3\frac{1}{8}$ in. length.



Rubber Research Glove

Dewey and Almy Chemical Co., 62 Whittemore Ave., Cambridge, Mass. This 38-in.-long neoprene rubber glove, developed for work in hermetically sealed dryboxes, permits the use of either hand in an armport and fits all average sized hands. The thin-gage material is claimed to provide touch sensitivity, dexterity, and full protection against contamination.



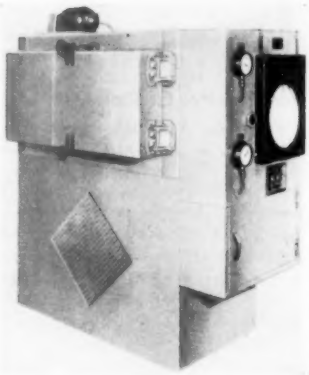
Power Supply

Ampex Electric Corp., Redwood City, Calif. The model 375 60-watt power supply is claimed to have frequency stabilization of 5 ppm per °C. Input may be 50–400 cycles and 99–125 volts; output is constant at 60 cycles and adjustable from 0 to 150 volts. Control panel embodies: voltage control, 0–150-volt a-c voltmeter, external oscillator input jack, and stroboscope supply socket.

Flowmeters

Technical Equipment Co., 4348 San Pablo Ave., Emeryville 8, Calif. Designed for metering small volumes of liquids and gases, the high-pressure meter will handle 1,000 psig, and the

low-pressure meter will handle 100 psig. Both models have maximum flow rates of 6–105 ml/min for water, and 90–610 ml/min for air at 20° C, depending on the type of float and size of tube used. Four sizes of tube and six different float materials are available. Neoprene gaskets are used in the low-pressure model; the high-pressure model may be obtained with neoprene or Teflon gaskets.



Test Cabinets

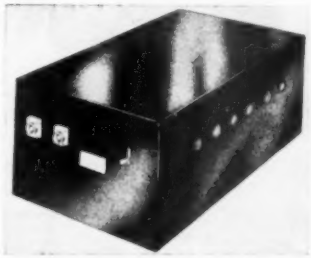
Standard Cabinet Co., 55 Washington Ave., Carlstadt, N. J. These controlled-humidity high- and low-temperature test cabinets have ranges from −150° to −200° F at 20–95% relative humidity. Units range in size from 1 to 75 cubic feet; special sizes are available up to 1,000 cubic feet. Electronic or pneumatic recording and indicating control systems are available. The cabinets have stainless-steel construction, full thickness insulation, vapor sealed inspection windows, optional interior illumination, and single or multi-stage refrigeration systems.

Electrical Delay Lines

Gulton Manufacturing Corp., 212 Durham Ave., Metuchen, N. J. These lines provide delays ranging up to 100 μsec, and are said to possess low-loss temperature stability. The delay lines are custom engineered to mechanical specifications and electrical characteristics. A typical line has a delay time of 1.1 μsec, an impedance of 460 ohms, and a rise time of 0.1 μsec, and is ¾ in. by ⅞ in. by 8⅛ in.

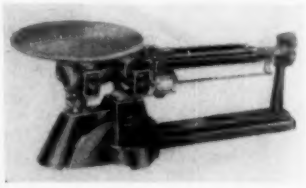
Portable Drying Unit

Electric-Aire Engineering Corp., 209 W. Jackson Blvd., Chicago 6, Ill. This dryer supplies 100 ft³/min of air at low speed and 150 ft³/min at high speed; its temperature range is 126° F at low speed, 114° F at medium speed, and 106° F at high speed. The 24-in. flexible hose remains in position until moved, and rotates in a 360-deg arc; the drying unit rotates in a 360-deg arc on its own axis. The dryer can be raised or lowered from 36 to 50 in. in height and operates on a-c or d-c. Special nozzles can be clipped to the standard 3⅝-in. hose. Drying unit is removable from portable stand for wall or portable table mounting.



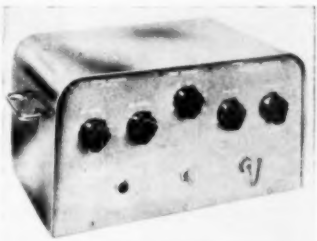
Transient Recorder

Magne-Pulse Corp., 140 Nassau St., New York 38, N. Y. Aperiodic, or one-shot, waveforms can be permanently recorded and then displayed at a desired repetition rate on an oscilloscope through the use of the type 102 magnetic transient recorder. The instrument provides a recording rate of up to 1,000 pulses per inch, or a bandwidth of 1 Mc. Any portion of the waveform can be displayed.



Triple-Beam Balance

Ohaus Scale Corp., 1050 Commerce Ave., Union, N. J. An undivided tare beam in this balance allows direct determination of the net value of the product being weighed. The empty container is balanced by use of the tare poise which can be locked on the tare rod. The balance capacity is 2,610 gm with a sensitivity of 0.1 gm. In addition to standard metric balance it can be supplied in avoirdupois or troy standards. Different types of weighing platforms, such as removable brass scoop or pan, can be supplied.



D-C Amplifier

Liston-Becker Instrument Co., Inc., 20 Beckley Ave., Stamford, Conn. The model 14 d-c breaker amplifier is designed for measuring d-c voltages and low-frequency a-c voltages in the microvolt range. Drift is said to be 0.005 μv per 8-hr day; gain stability is said to be 0.3% per 8-hr day for a stable power line, over-all gain variation is 0.5% for a line-voltage variation of 10%. The amplifier is linear to within 2 volts when terminated into 500 ohms, and to within 4 volts when used with an infinite-impedance meter. The input transformer can be designed

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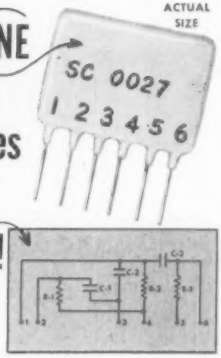

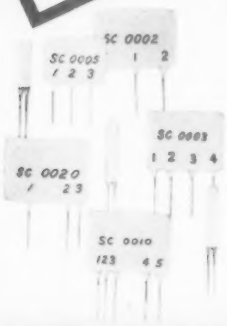

Stupakoff printed circuits save space and weight, speed assembly, reduce costs, minimize assembly errors. Soldered connections are reduced by 25% to 80%, assemblies are lighter and more compact, your production time is reduced and better products are made when Stupakoff Printed Circuits are used. These sturdy, compact, accurately produced units combine resistors and capacitors of precision values, in circuits designed in accordance with the requirements of individual applications. Write for Bulletin.

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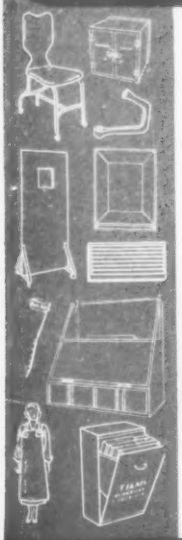

RADIUM STORAGE SAFE

Constructed of heavy cast and machined lead, radium storage safes are designed and fabricated in many sizes to meet individual therapy requirements.

At left is shown a portable radium unit for carrying radium from safe to place of therapy. Also shown is a radium screen for viewing radium handling operations.

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Stainless Steel Processing Systems
Thermostatic Valve Assemblies
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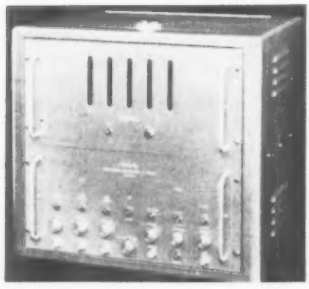
for any given impedance between 5 and 100,000 ohms. The 20-position coarse control changes 4 db per position; the fine gain control permits interpolation between these positions. Bucking potentials up to 100 μv may be used.

Fundamental Oscillator

Polytechnic Research and Development Co., 55 Johnson St., Brooklyn, N. Y. The type 907 oscillator is continuously tunable over the frequency range of 35-900 Mc/sec and has a 30-to-1 tuning range with an output voltage of not less than 1 volt across 75 ohms at all frequencies. Introduction of an external frequency marker is provided for. A sinusoidally vibrating tank capacity provides a swept width of not less than 10 Mc/sec for a center frequency of 35 Mc/sec. The frequency deviation is greater than 20 Mc/sec for carrier frequencies above 60 Mc/sec. An attenuator permits continuous adjustment of the output voltage from 10 mv to 1 volt at all frequencies.



Counter and Timer

Berkeley Scientific Corp., 2200 Wright Ave., Richmond, Calif. The model 550 universal counter and timer can be used as a frequency measuring device, an electronic tachometer, a secondary frequency standard, or a means of measuring the ratio of two independent variables. Ranges are

0–100,000 cps, and 10 μsec to 1 sec, accurate to within ±10 μsec. This model is claimed to have a stability of better than 1 part in 10^5. Input requirements: for the events-per-unit-time channel, any positive wave shape of amplitude 0.2–50 volts rms; for the time interval pulse channel, either positive or negative pulses with a rise time of 1 volt per μsec or better; for the time interval photowave channel, a maximum sensitivity of 0.5 volt rms and either positive or negative waves. The decimal presentation has a time base selectable as 0.1, 1.0, and 10 sec. By the use of auxiliary photocell attachments, the interval between two light flashes may be timed, or the duration of a light flash or a dark period may be determined with an accuracy of ±10 μsec.

Portable Power Supply

Saga, Inc., 1015 Diamond Ave., Evansville, Ind. This supply operates from 105–125 volts, 50–60 cycles, and provides an output of 0–2,000 volts at 1 ampere, maximum, with overload trip selection at 25, 50, 100, 500, 650, 800, and 1,000 ma. Other voltages are obtainable. Power unit has continuously variable voltage output, Variac-controlled automatic reset, auxiliary circuit protection, and positive or negative output.

B_4C Mortar and Pestle

Robert Marks Co., 47 Goddard St., Providence, R. I. The extreme hardness and self-bonding of boron carbide minimize contamination due to abrasion of the mortar parts. It also possesses high resistance to attack by chemicals. The fact that boron lines are few is advantageous in spectrographic analysis. Mortars of $\frac{3}{4}$ and $1\frac{1}{4}$ in. diameters are available, with one or two cavities. The cavity surface is either highly polished or fine

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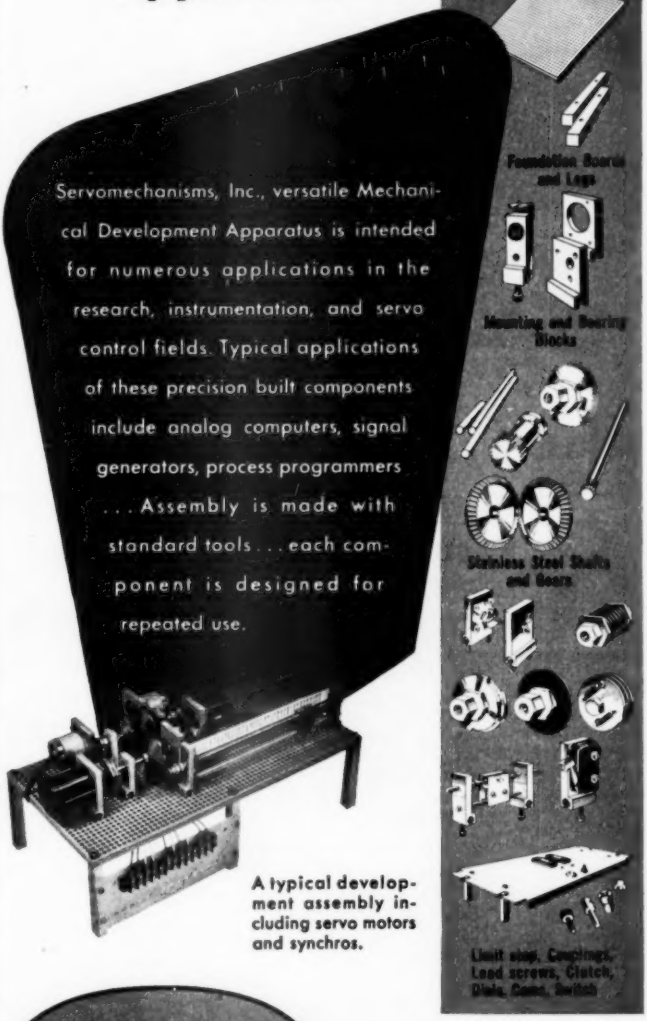
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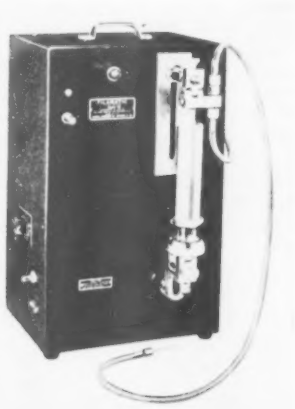
matte; mortar is set in plastic base with push fit allowing it to be removed for cleaning. The pestle is an hexagonal aluminum rod to which is attached a boron carbide tip of $^{7}/_{16}$ or $^{1}/_{4}$ in. diameter.



Automatic Filler

Scientific Glass Apparatus Co., Inc., 100 Lakewood Terr., Bloomfield, N. J. This automatic pipette and vial filling machine dispenses liquids at speeds variable from 10 to 90 deliveries per minute. The device covers the range from 0.025 to 50 cm^3. Design of the delivery tip is said to prevent hanging drops. All liquid-contacting parts are of stainless steel.

Electronic Timer

Farmer Electric Co., 21 Mossfield Rd., Waban 68, Mass. The type CK, models C and D, timers have four ranges: 1.5, 3, 6, or 12 sec. A dial with 100 graduations allows timer to be set for any percentage of total

fused quartz

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range. Contacts handle 8 amperes and may be used for controlling separate load as well as for momentary starting duty. The timer, using a cold-cathode trigger tube, can be started by either momentary or sustained contact and can be recycled immediately, with no delay for recharging a timing capacitor.

Tubing

Irvington Varnish and Insulator Co., 6 Argyle Terrace, Irvington 11, N. J. The class H silicone-rubber-coated Fiberglas tubing is said to have exceptional flexibility from −60° to 180° C and to stand exposure of 200 hr at 200° C without embrittlement. At 25° C a minimum average breakdown voltage of 7,000 is obtainable with grade H-A-1. The tubing is limited to applications which do not require good chemical or abrasion resistance; it absorbs 5–10% water after 24-hr immersion at room temperature. Sizes 0–20 and 24 are available in lengths up to 36 in.

INDUSTRY NOTES

▶**Arthur D. Little, Inc.,** 30 Memorial Dr., Cambridge 42, Mass., has announced the election of Allen Latham, Jr., as a vice president. Mr. Latham will continue as technical director of the mechanical division. Leroy F. Marek was named to the board of directors; he will have charge of technical operations. Franklin E. Satterthwaite has joined the operations research group.

▶**Vacuum Metals Corp.** has been formed as a wholly-owned subsidiary of the National Research Corp., 70 Memorial Dr., Cambridge, Mass. The new company will undertake commercial exploitation of some of the parent company's developments in metallurgy.

▶**Arma Corp.,** 254 36th St., Brooklyn 32, N. Y., has formed a financial division to be directed by David F. Devine, who was elected a vice-president of the concern.

▶**Industrial Nucleonics Corp.,** 1205 Chesapeake Ave., Columbus 12, Ohio, has announced the completion of its new research and engineering building. The radiochemistry division will also be housed in the new building.

▶**Nuclear Measurements Corp.,** Indianapolis 5, Ind., recently moved into

NEW SAFETY-DESIGN FUME HOOD for handling Radioactive Isotopes

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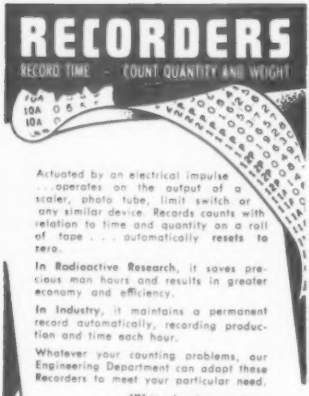
RECORD TIME — COUNT QUANTITY AND WEIGHT



Actuated by an electrical impulse . . . operates on the output of a scaler, photo tube, limit switch or any similar device. Records counts with relation to time and quantity on a roll of tape . . . automatically resets to zero.

In Radioactive Research, it saves precious man hours and results in greater economy and efficiency.

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Whatever your counting problems, our Engineering Department can adapt these Recorders to meet your particular need.

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a new plant at 2460 N. Arlington Ave. The new building gives the company 6,400 ft² of space. For future expansion, the company owns three additional acres behind the plant.

LITERATURE AVAILABLE

Radiation instruments. Technical data sheets describe monitors, G-M tubes, and proportional counters. *Nucleonic and Radiological Developments, Ltd., 77 King's Rd., London, S. W. 3, Eng.*

Instruments. Bulletin 15-14 illustrates uses of measuring instruments. *Minneapolis-Honeywell Regulator Co., Industrial Division, Philadelphia 44, Pa.*

Electrometer. Technical data sheet describes vacuum-tube electrometer. *Keithley Instruments, 3868 Carnegie Ave., Cleveland 15, Ohio.*

Magnetic measurements. Bulletin GEC-777 tells about equipment for measuring magnetic properties. *General Electric Co., Schenectady 5, N. Y.*

Pyrometers. Bulletin G-2 shows controlling pyrometers and related equipment. *Assembly Products, Inc., Chagrin Falls 5, Ohio.*

Metal walls. Catalog 52 contains information on movable metal walls. *Mills Co., 975 Wayside Rd., Cleveland 10, Ohio.*

Relays. Bulletin T-2 gives data on time-delay relays. *Cook Electric Co., 2700 Southport Ave., Chicago 14, Ill.*

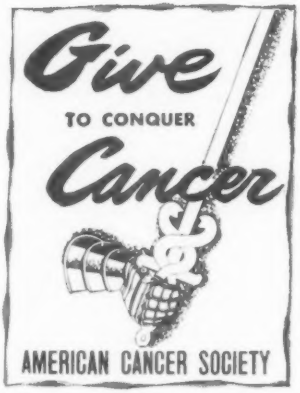
Resistance units. Technical bulletin 13 gives characteristics of negative-temperature-coefficient resistance units. *Keystone Carbon Co., St. Marys, Pa.*

Speed changers. Technical data sheet 7 describes antibacklash miniature speed changers. *Metron Instrument Co., 432 Lincoln St., Denver 9, Colo.*

Galvanometers. Section ED of catalog E shows line of galvanometers, dynamometers, and accessories. *Leeds and Northrup Co., 4934 Stenton Ave., Philadelphia 44, Pa.*

Plastic lubricants. Technical bulletin 5-1-52 gives information on Kel-F oils, waxes, and greases. *M. W. Kellogg Co., Chemical Manufacturing Division, Box 469, Jersey City 3, N. J.*

Potentiometers. Bulletin P1245 describes line of electronic potentiometers and bridge instruments. *The Bristol Co., Waterbury 20, Conn.*



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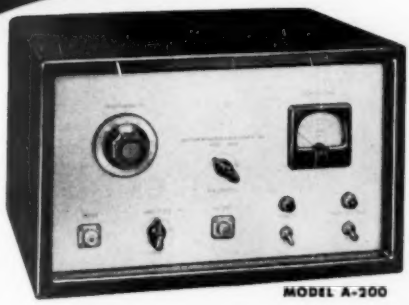

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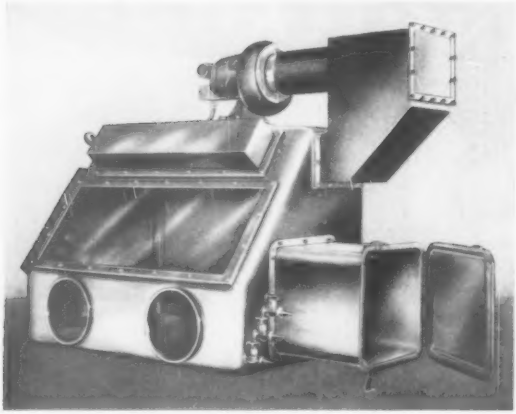

Above: **LOW INTENSITY DRY BOX** — Designed for the safe handling of radioactive materials. Also useful for work with bacteria, viruses and other hazardous substances. Other types of enclosures available include vacuum dry boxes, biological safety cabinets and research enclosures, and a complete interchangeable dry box system.

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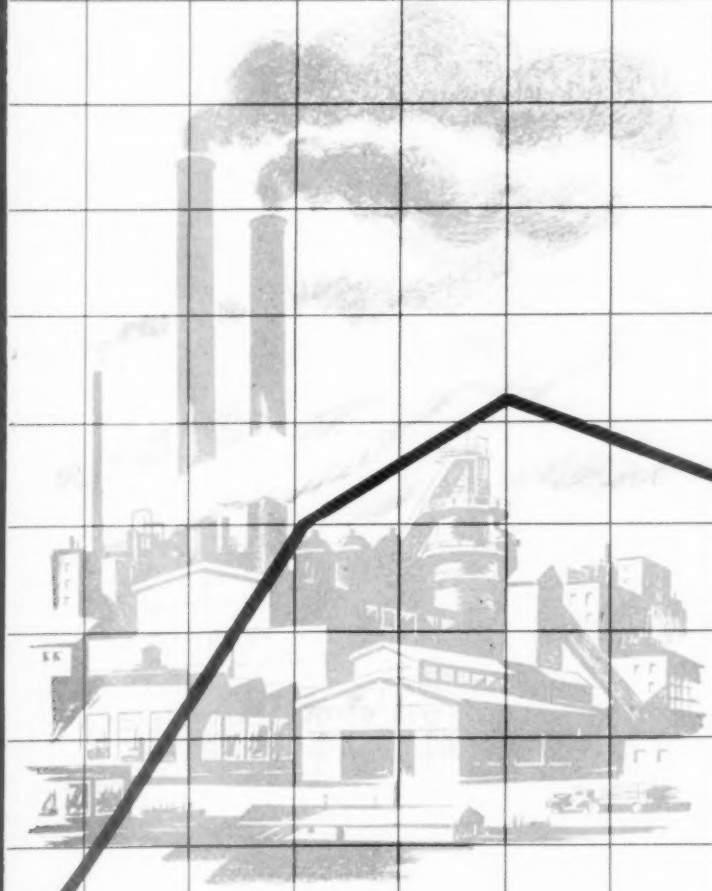
INDUSTRY'S ROLE IN ATOMIC ENERGY



A NUCLEONICS SPECIAL REPORT

The story has been told many times of how the foothills of Tennessee, the mesas of New Mexico and the deserts of Washington were converted from nothingness into the first fabulous factories of the atomic age. The drama of powerful weapons, of nuclear-propelled planes and ships, of radioisotopes has been related.

But one story has never been told—of how all American industry has been affected by the mushrooming atomic energy program. To do its job, the U.S. Atomic Energy Commission has had to call upon thousands of companies. In the following pages, NUCLEONICS spells out the details of what the impact of the program has been on industry.

WHAT IS THE ATOMIC ENERGY INDUSTRY? Perhaps its principal characteristic is that it is difficult to define. Different from other industries, this one is not yet very homogeneous. It includes thousands of companies of all types—chemical, electrical, construction, etc.

What then is it that they have in common? Stated simply, it is that they do research, design, development and construction work on or in plants and laboratories using atomic energy processes. Or they sell equipment and products to such plants and laboratories.

There are two types of companies which fit the above description—(1) those working as or for contractors in the Government's atomic energy program and (2) those using atomic energy processes, products or machines in their own businesses. Some companies do both.

To date, almost all of the money spent has come out of Uncle Sam's pockets and has gone to companies in category 1. The real atomic energy industry—one in which industry spends its own money—is only now beginning to pick up momentum. Ultimately this real industry will far outstrip the Government-supported program.

This report is primarily concerned with how $6.5-billion has been spent on atomic energy in ten years. Special emphasis has been placed on one two-year period, fiscal years 1950 and 1951. For this period, contract awards were summarized according to contract size, type of work, type of business, type of contract and method of award of contracts. In addition, of four types of work performed under AEC contract, one—supply—has been analyzed to show how expenditures were distributed through 41 different industries.

How the AEC Operates

The basic pattern of operation established by the Manhattan Engineer District during the war has been followed by the AEC since it took over in 1947. This, simply, has been to place in the hands of private industry the principal chore of designing, building and operating the major plants. The responsibility of Government employees has been to set policy, obtain contractors and administer the program. This is demonstrated by the chart on this page which shows the distribution of workers between Government and industry.

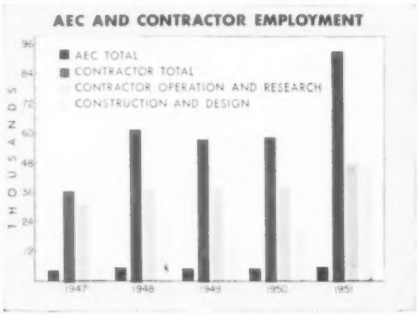
Three basic types of contracts are used by the AEC:

1. Unit price—used in purchasing supplies, materials and other equipment.
2. Lump sum—used principally for construction work where a concern agrees to do a job for a fixed price. Sometimes used for architect-engineer design and other service and supply contracts.
3. Cost—used for operations in Government-owned plants, and other facilities, for large development undertakings such as those for new kinds of nuclear reactors, and for particular construction jobs. Sometimes the contractor receives a fixed fee in addition to his costs.

Work done for the AEC is divided into four categories:

1. Supply—this includes equipment, supplies and services.
2. Construction.
3. Research and development—this includes raw materials, fissionable materials, weapons, reactor development, physical research, and biology and medicine.
4. Other.

In the charts in this report, a company has been included in the "small business" category if its position in the trade or industry of which it is a part is not dominant, the number of its employees does not exceed 500, and it is independently owned and operated.



Manhattan Project—the Wartime Program

Keynote of the work of the Manhattan Engineer District under the Army Corps of Engineers was speed. The program started in wartime, and, if an atomic bomb was to be produced, it had to be made fast, ahead of the enemy.

Long-range planning was unimportant. Fissionable materials had to be obtained in sufficient quantities to be used in bombs. Unexplored areas of science and technology had to be charted. Thus, where there was any difference of opinion or lack of certainty as to the selection of a process, more than one was tried.

In a period of about three years, nearly $2-billion was spent in building up a vast and complex manufacturing and research enterprise. Very diversified facilities were set up at three centers:

1. Oak Ridge. By August, 1945, $1,106,400,000 was spent to develop a pilot plant for the production of plutonium and effective production processes for the separation of U^{235}. The principal contractors were:

a. Gaseous diffusion separation plant (K-25). Kellex Corp. (Vitro Corp.), basic process design; Ford, Bacon and Davis, design, construction and operation of auxiliary plant for testing equipment; J. A. Jones Construction Co., erection of K-25 at cost of $500,000,000; Carbide and Carbon Chemicals Corp., operation of K-25.

Other important companies involved included: Chrysler Corp., Allis-Chalmers, American Machine Defense Corp., Valley Iron Works, F. J. Stokes Machine Co., Westinghouse, National Research Corp., Midwest Piping and Supply Co., Houdaille-Hershey Co., Taylor Instrument Co., General Electric Co., Pacific Pump Works, duPont, Harshaw Chemical Co., Hooker Electrochemical Co., Mallinckrodt Chemical Works.

b. Electromagnetic separation plant (Y-12). Stone and Webster Engineering Corp., design and construction of plant at cost of $472,000,000; Tennessee Eastman Corp., operation of plant; manufacturers and suppliers of equipment included General Electric, Westinghouse, Allis-Chalmers, Link-Belt Co., etc.

c. Plutonium pilot plant (X-10).
DuPont built and operated this plant which cost $13,000,000.

d. Thermal diffusion.
H. K. Ferguson Co., architect-engineer-manager of this plant which cost $10,500,000; Fercleve Corp., subsidiary of Ferguson, operated plant.

Subcontractors included: Edenfield Electric Co., Turner and Ross Co., Pittsburgh Pipe and Equipment Co., National Valve Co., Tri-State Asbestos Co., Tennessee Roofing Co., Pacific Pump Co., Westinghouse, Mehring and Hanson Co., and Grinnel Corp.

2. Hanford. Built and operated by duPont; cost $350,000,000.

3. Los Alamos. Operated by University of California as bomb research development and production center. Plant built by M. M. Sundt and R. E. McKee; cost $59,400,000.

First Expansion under AEC

Because the wartime plants had to be built in a great hurry, they were not designed for long life. Therefore, when the AEC took over in 1947, it had a major task of rejuvenating, rebuilding and replacing many of the old plants, in addition to building some completely new ones.

Spending more than $700-million, AEC carried out the greatest single construction program in peacetime history. Much of the work was centered at the Hanford Works, whose operation was taken over from duPont by General Electric.

During this expansion, 20 plants were either newly constructed or underwent major alterations. Fissionable-materials production was extended into 15 states, with work being carried on in 30 separate plants at 25 different locations. Major repairs were made on the three wartime reactors at Hanford, and new ones were built there.

At Hanford, GE was the operating contractor with the Atkinson-Jones Construction Co. as the principal construction contractor.

Feed-materials plants were repaired and improved by more than 30 contractors, including Battelle Memorial Institute, Electro Metallurgical Co., Harshaw Chemical Co., Linde Air Products Co., Mallinckrodt Chemical Works, and Vitro Mfg. Co.

New chemical separation facilities were built, with the following companies contributing to the work: GE, Standard Oil Development Co., Carbide and Carbon Chemicals Corp., Kellex Corp. (now Vitro Corp.), Blaw-Knox Co., Monsanto Chemical Co., Dow Chemical Co., and duPont.

Second Expansion—Now under Way

This expansion, much larger than the previous one, was stimulated by the outbreak of the Korean war in June, 1950. Work has centered principally at two places—Paducah, Ky., and Savannah River, S. C. At Paducah, new gaseous diffusion facilities are being built by the F. H. McGraw Co., with Carbide to be the operator. At Savannah River, duPont is building a group of reactors which may be used to produce hydrogen bomb materials.

Perhaps the best way to illustrate work done in this expansion is to list a number of projects which were included in AEC's budget recommendations for 1951.

PRODUCTION

1. Classified projects—$3,837,000.
2. Permanent decontamination facilities, K-25, Oak Ridge—$100,000.
3. Miscellaneous construction, K-25, Oak Ridge—$740,000.
4. K-27 stage revision, Oak Ridge—$800,000. To increase capacity of process, new impellers placed on pumps, high horsepower motors replaced small motors.
5. Barrier pilot plant, K-25, Oak Ridge—$80,000.
6. Miscellaneous plant and equipment improvements, Y-12, Oak Ridge—$437,450.
7. Motor drives, for pile area blowers, Hanford—$50,000.
8. Replacement of process piping, pile areas, Hanford—$130,000.
9. Technical center, Hanford—$5,038,000. New radiochemistry, radiophysics, radiometallurgy and radiobiology laboratories, plus certain improvements.
10. Waste storage facilities, Hanford—$2,700,000. New tanks for radioactive wastes.
11. Automatic flow valves, Hanford—$40,000.
12. Pile loading equipment, Hanford—$45,000.
13. Uranium discharging facilities, Hanford—$135,000.
14. Waste disposal facilities, Hanford—$23,000.
15. Air-filtering equipment, Hanford—$28,000.
16. Waste concentration evaporators, Hanford—$500,000.
17. Equipment for metallurgical control of uranium slug fabrication, Hanford—$160,000.
18. Radiation detection instruments, Oak Ridge—$100,000.
19. Heavy-water production plant—$4,500,000. Principal items of equipment include: large reciprocating-type compressors; hydrogen gas expansion turbines to provide refrigeration; reversing-type heat exchangers; large primary distillation aluminum tower; welded aluminum piping.
20. Plant and mining equipment, Colorado—$62,600
21. Radiation detection instruments and components, equipment for instrument laboratory, New York—$150,000.
22. Scientific laboratory equipment and apparatus, New Brunswick—$31,000.
23. Movable equipment, K-25—$481,500. Mechanical and electrical operating and control equipment, including stage pumps, coolers, cooling pumps, blowers, valves, motors, transformers, etc.
24. Radiation instruments, Oak Ridge—$11,320.
25. Nonradiation instruments, Oak Ridge—$7,750.
26. Miscellaneous equipment, K-25—$453,590. Includes 156 100-HP motors at $1,265 each.
27. Plant equipment, Hanford—$505,000. Includes such things as: laboratory and clinical centrifuges, strip heaters and rheostats, electrolytic equipment, microscopes, physics equipment, tisselius and warburg apparatus, instrument testing equipment, etc.

PHYSICAL RESEARCH

1. Research laboratory, Ames Laboratory—$100,000.
2. Research reactor, Argonne—$2,000,000.
3. Particle accelerator, Berkeley—$1,325,000.
4. Laboratory facilities development, Berkeley—$375,000.
5. Engineering laboratory, Brookhaven—$100,000.
6. Reactor additions and adjustments, Brookhaven—$120,000.
7. Waste concentration plant, Brookhaven—$250,000.
8. Cosmotron and building, Brookhaven—$300,000 (total cost to be about $4,000,000).
9. New and renovated research facilities, Oak Ridge National Laboratory—$1,375,000.
10. Plant and equipment improvements, Oak Ridge National Laboratory—$1,373,000. Includes radiation instruments, other instruments, lab equipment other than instruments, major apparatus, rabbit farm, etc.
11. Linear accelerator, Berkeley—$5,000,000.
12. Laboratory equipment, Ames—$11,000.
13. Radiation instruments and shop equipment, Oak Ridge—$68,000.
14. Health physics instruments, Oak Ridge—$23,000.

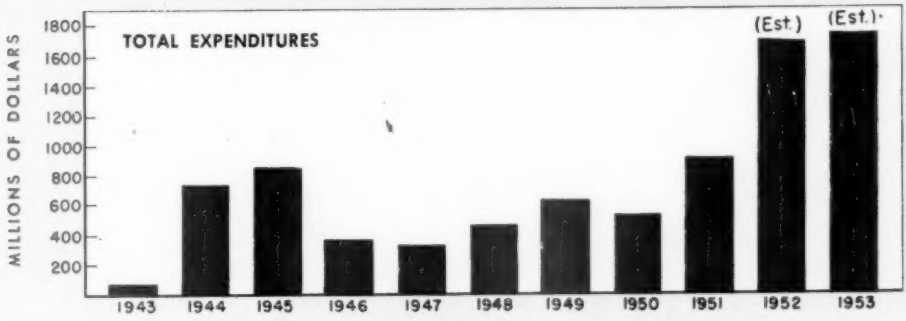
BIOLOGY AND MEDICINE

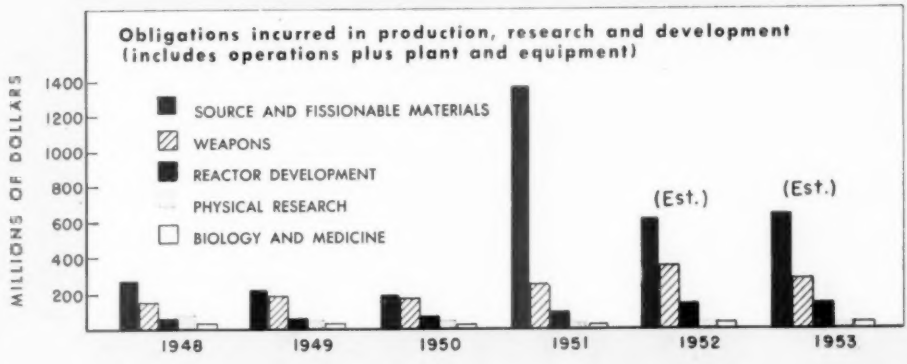
1. Automatic counting room, Hanford—$25,000.
2. Biology research building, Argonne—$5,750,000.
3. Cancer hospital, Chicago—$475,000.
4. Animal laboratory, Brookhaven—$150,000.
5. Maintenance and alterations of facilities, Brookhaven—$325,000.
6. Laboratory equipment, Oak Ridge—$10,000.
7. Livestock, Oak Ridge—$1,800.

FINANCIAL SUMMARY

OF ATOMIC ENERGY EXPENDITURES

1943—1953





8. Meteorological equipment, Oak Ridge—$28,000.
9. Radiological laboratory equipment, New York—$20,000.
10. Scientific laboratory equipment, Brookhaven—$362,000.

REACTOR DEVELOPMENT PROGRAM

Total operations, reactor research and development—$37,516,420; reactor projects—$21,726,000; applied research & development—$15,790,420.

Breakdown of applied research and development costs:

1. Development of materials and components—$6,000,000.
2. Development of separations systems—$3,629,000.
3. Development of waste-treatment systems—$1,473,000.
4. Environment engineering projects—$275,000.
5. Development of heat transfer systems—$2,730,000.
6. Reactor physics—$1,062,000.
7. Test station, Arco, Idaho—$550,000.

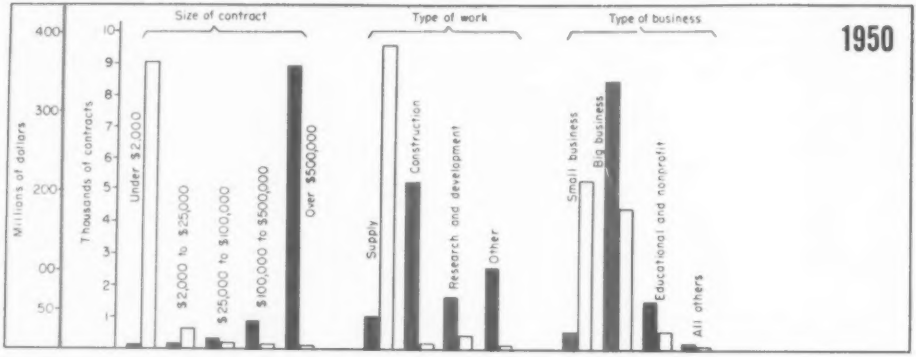
Reactor research:

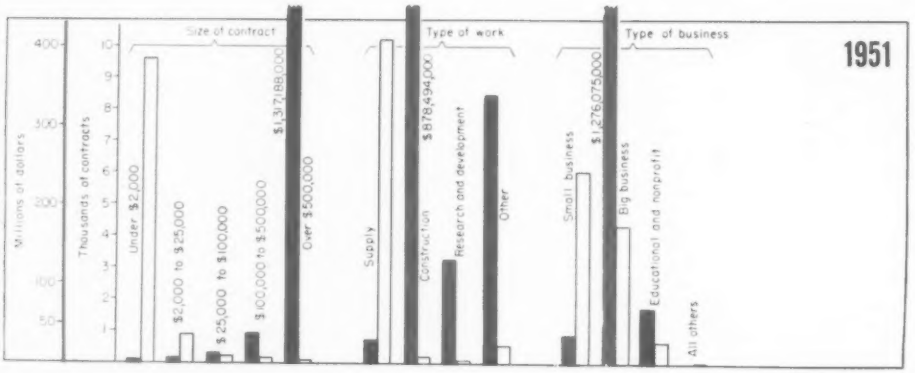
1. Laboratory and plant equipment, Argonne—$664,000.
2. Laboratory equipment, Battelle Memorial Institute—$9,400.
3. Laboratory and shop equipment, North American Aviation—$50,500.
4. Laboratory and shop equipment, Knolls Atomic Power Laboratory—$685,000.

SUMMARY OF CONTRACT

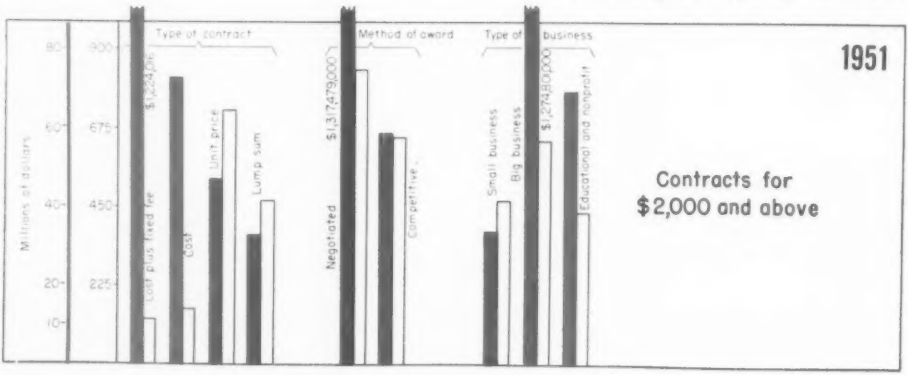
PRIME CONTRACTS

According to Size of Contract,





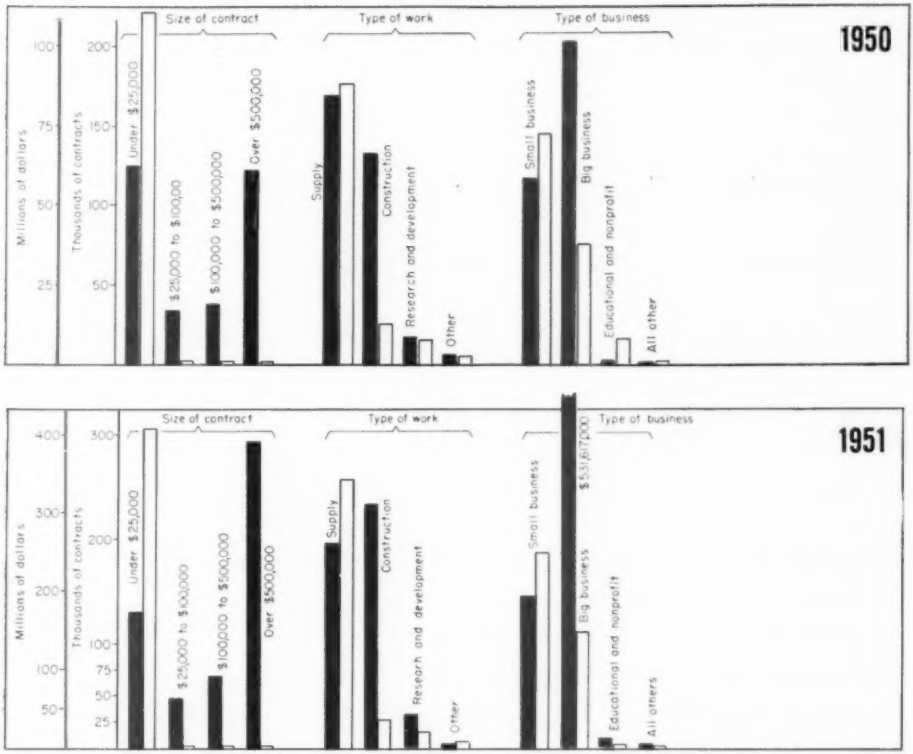
According to Type of Contract,



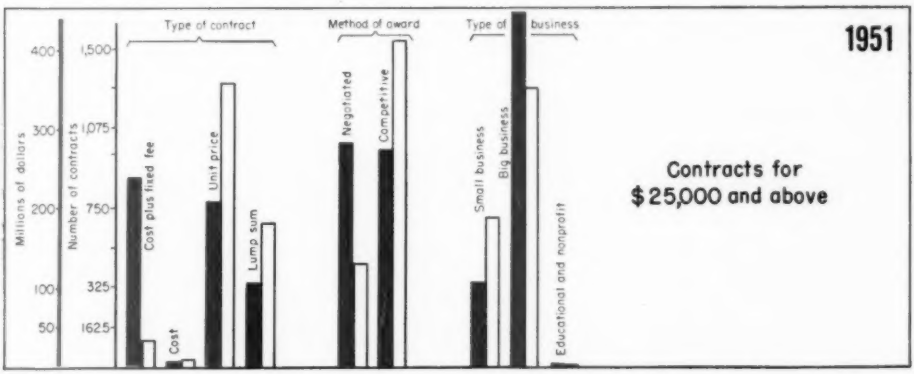
AWARDS FOR 1950 & 1951

SUBCONTRACTS

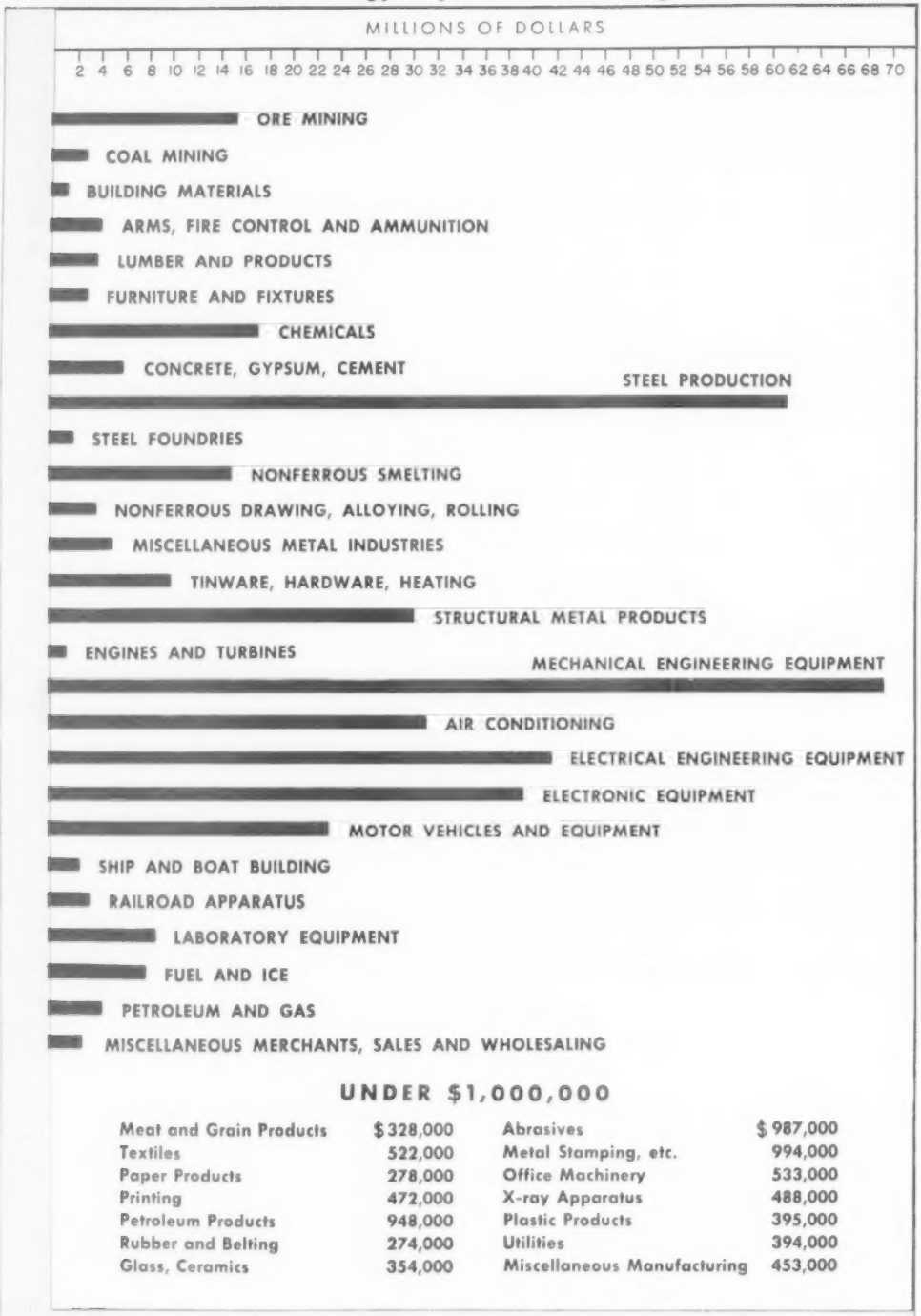
Type of Work, Type of Business



Method of Award, Type of Business



Distribution of Atomic Energy Expenditures through American Industry



UNDER $1,000,000

Meat and Grain Products	$328,000	Abrasives	$987,000
Textiles	522,000	Metal Stamping, etc.	994,000
Paper Products	278,000	Office Machinery	533,000
Printing	472,000	X-ray Apparatus	488,000
Petroleum Products	948,000	Plastic Products	395,000
Rubber and Belting	274,000	Utilities	394,000
Glass, Ceramics	354,000	Miscellaneous Manufacturing	453,000

DETAILED BREAKDOWN FOR THIRTY-NINE INDUSTRIES

[In Millions of Dollars]

To determine the impact of the vast atomic energy program upon American industry, nearly 3,000 contracts labelled "supply" or "equipment" and either in operation in June 1949 or put into operation between July 1, 1949, and June 30, 1951, were examined. Contracts for "construction," "operation," "research" and other categories were omitted since they involve far fewer individual contractors than the contracts for supply or equipment.

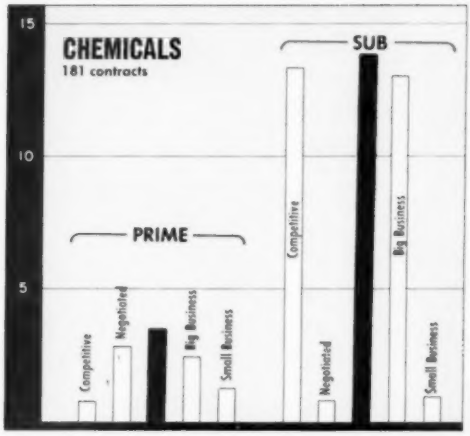
The charts on the following pages show how the expenditures for supplies or equipment are broken down among 41 industry groups as defined by the Bureau of Budget "Standard Industrial Classification Manual." On the left is a summary chart.

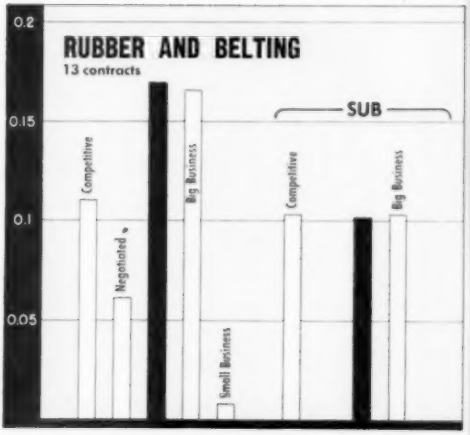
The prime contracts involve amounts of $2,000 each and above; the subcontracts $25,000 each and above. This limitation was imposed by the fact that detailed data below these levels were not available. Because analysts lacked information describing many contracts of a supply nature in amounts above these levels, summaries arrived at are also limited to this extent; however, the samplings obtained can be considered significant.

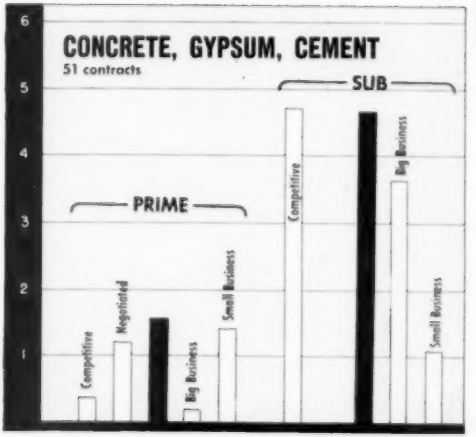
In the years surveyed here, the total expenditure in the equipment-supply category was $521,233,928 distributed among 454,937 contracts. The analysis presented here represents nearly 85% of the money but, because of the limitation mentioned, less than 1% of the number of contracts. Since it is known that a high per cent of these many small contracts is let on a competitive basis to small business, it can be assumed that their omission from the accompanying tabulations results in summaries favoring the negotiated type contract and "big business" in greater ratios than would an analysis of all AEC contracts.

In no case does the allocation of a particular manufacturer to a particular industrial category indicate what the manufacturer sold; this knowledge is bound up in necessary security. In fact, where certain large companies are involved, companies engaged in several industries, an arbitrary decision was made and the contract data was allocated to the type of industry most often associated with the given manufacturer.

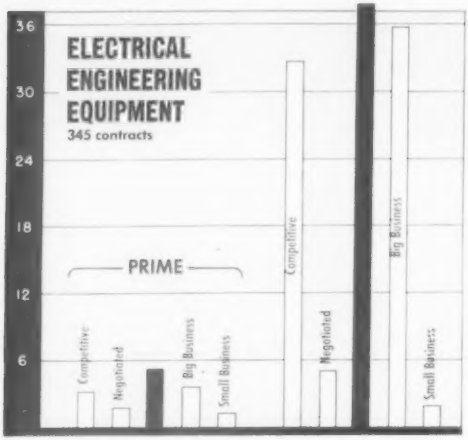
The charts show not only the distribution of the contract sums among industries but also show the relation between prime and subcontracts, whether the contracts were let on a "negotiated" or "competitive" basis, and how the total dollar volume was shared by big and small business.

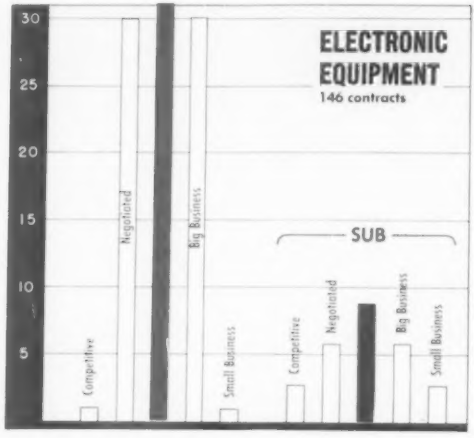


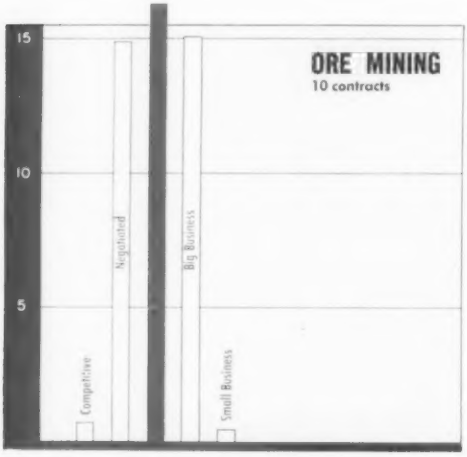


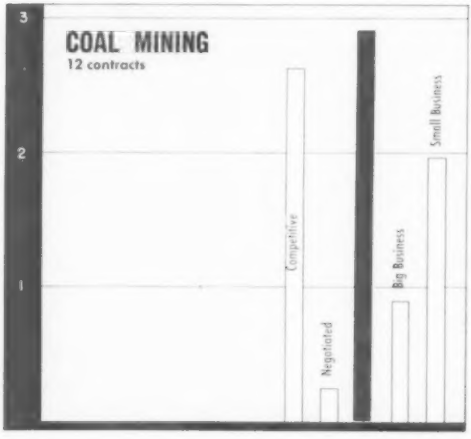


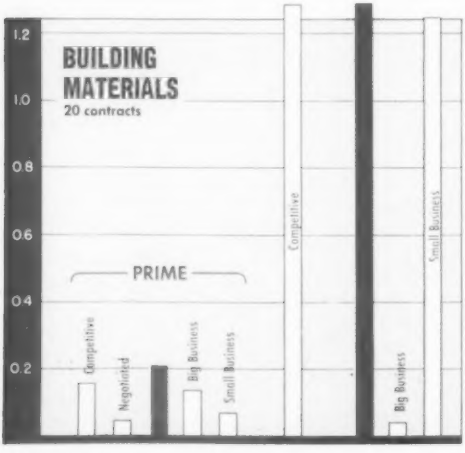
DETAILED BREAKDOWN IN MILLIONS OF DOLLARS (Continued)

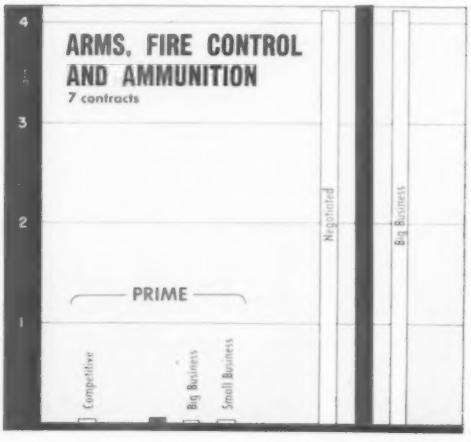












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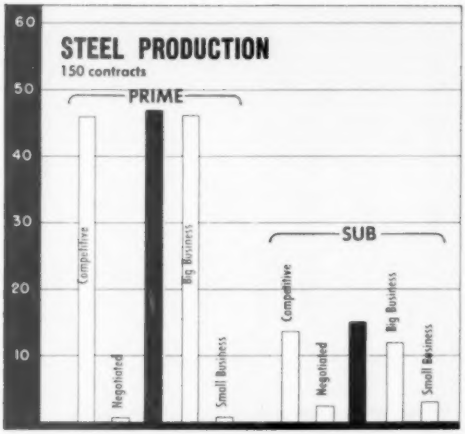

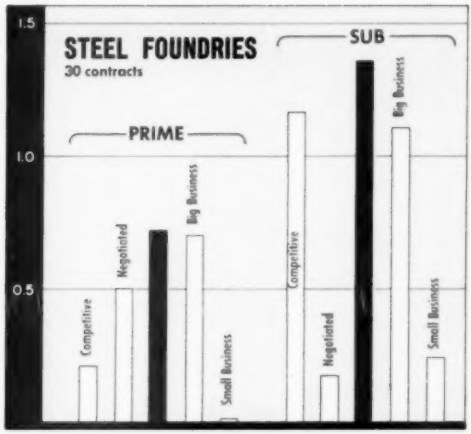

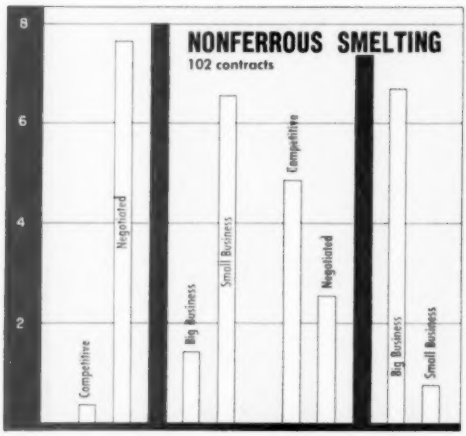

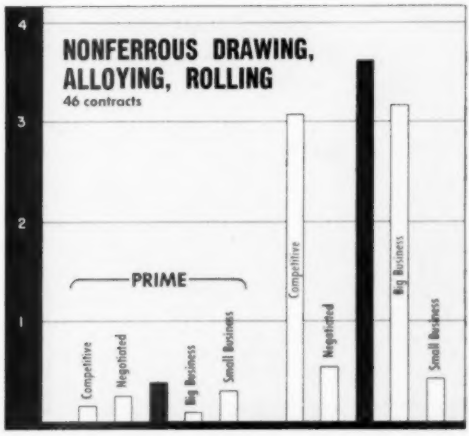

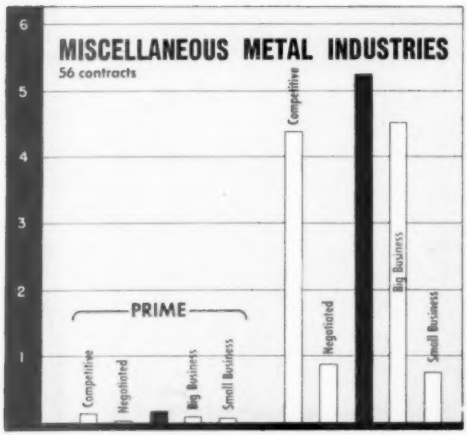

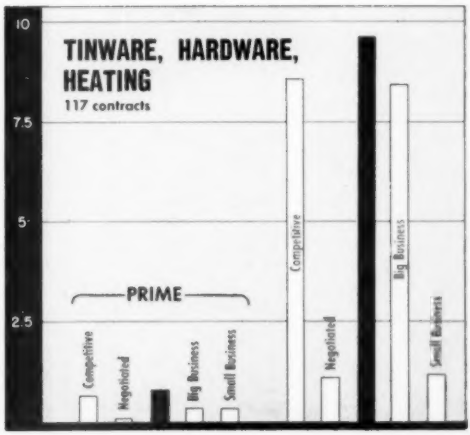

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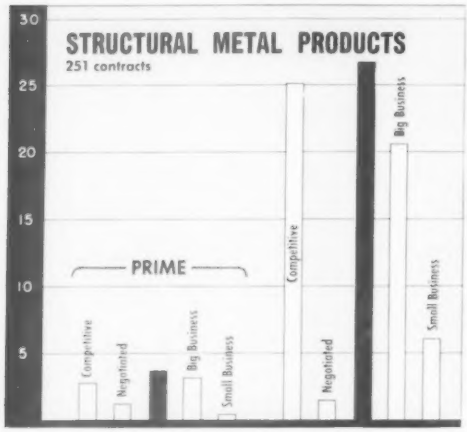

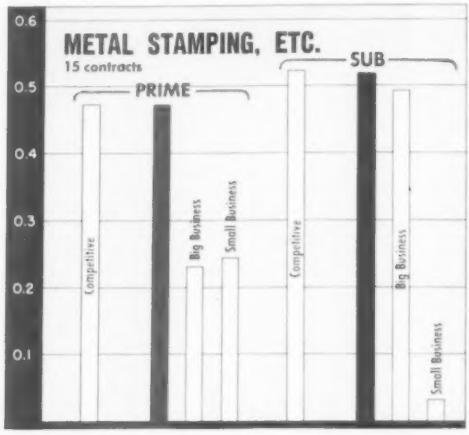

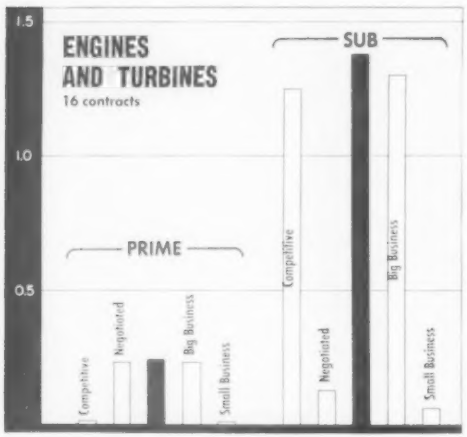

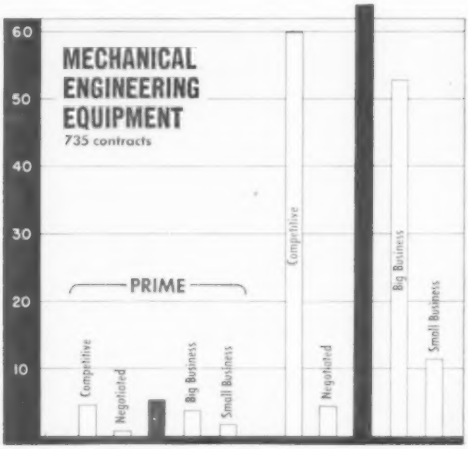

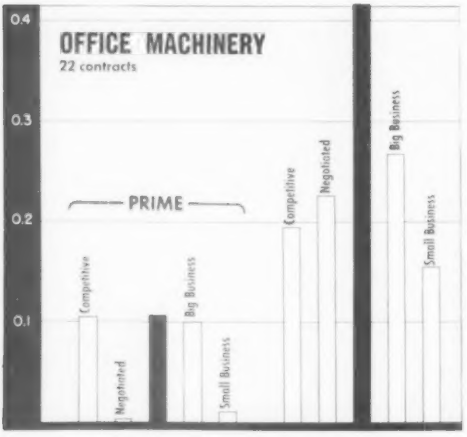

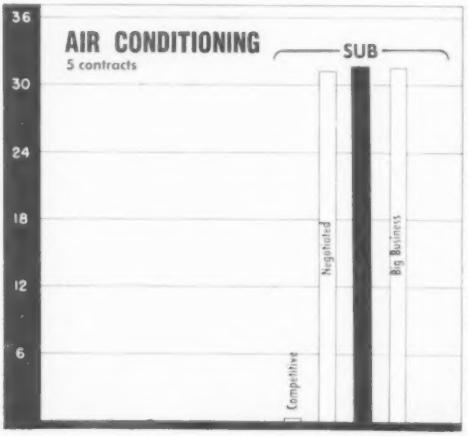

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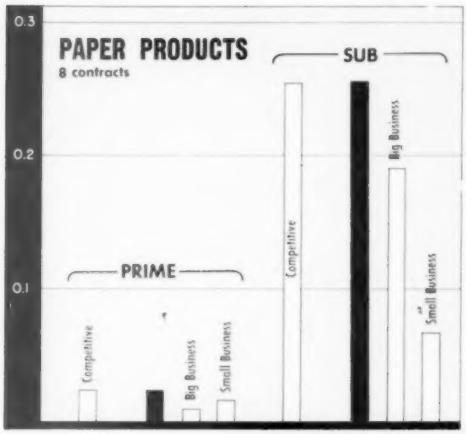

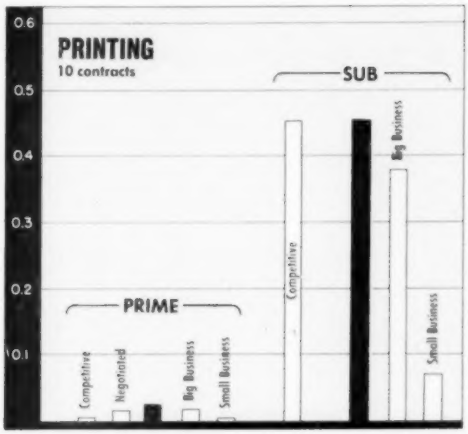

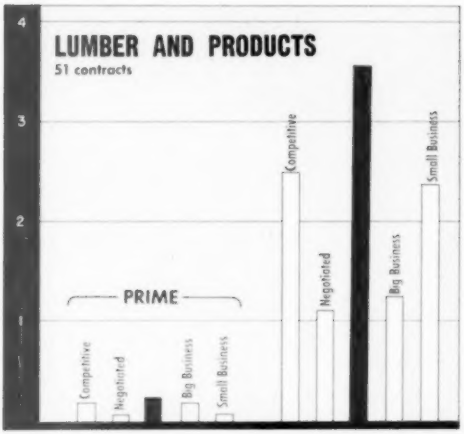

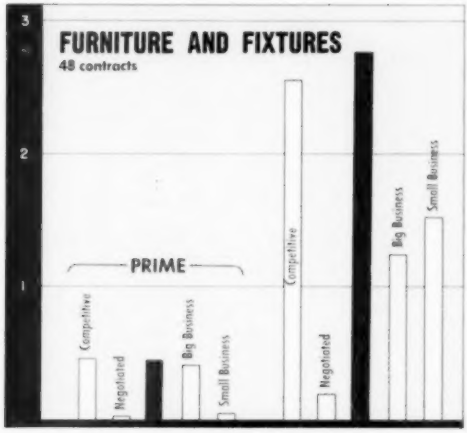

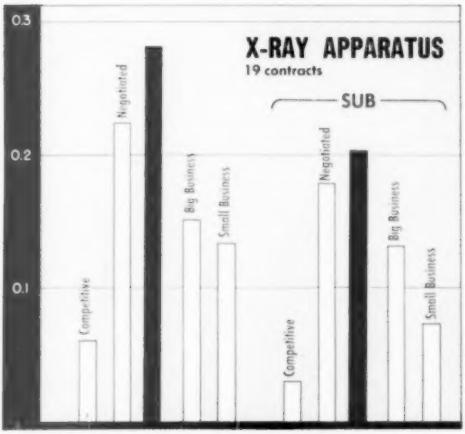

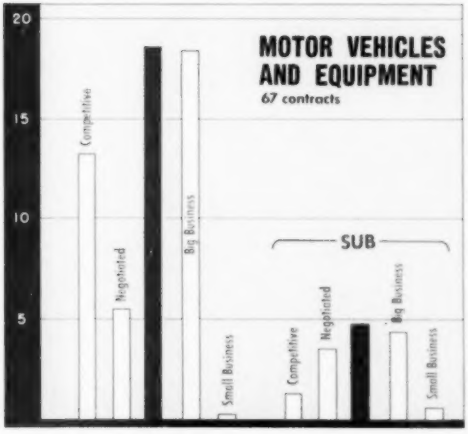

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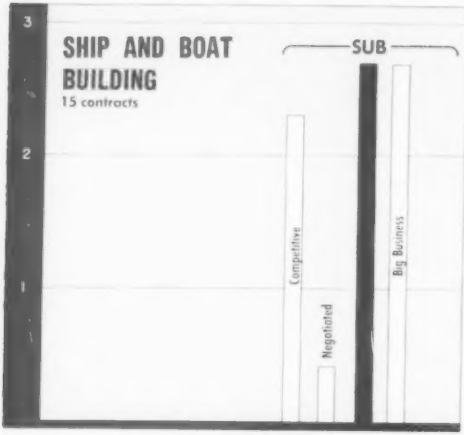

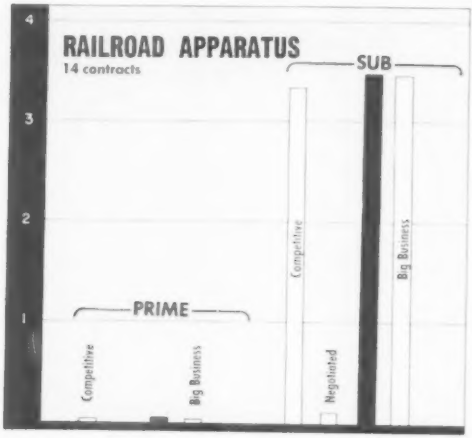

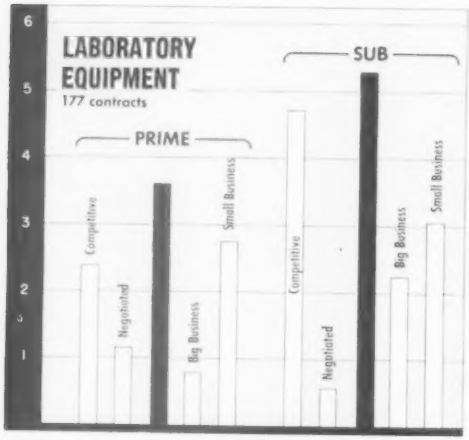

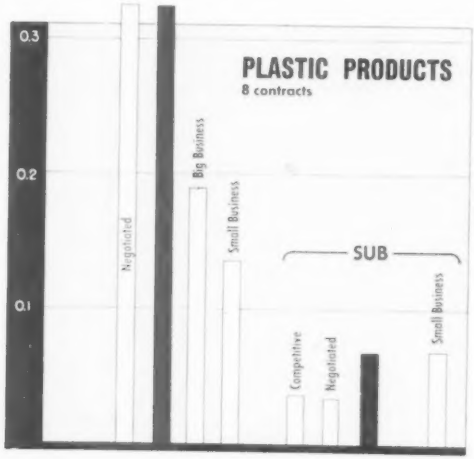

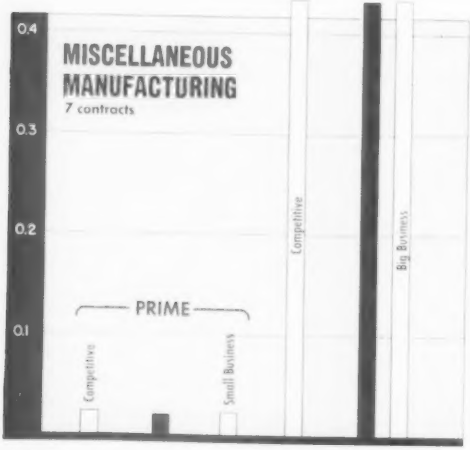

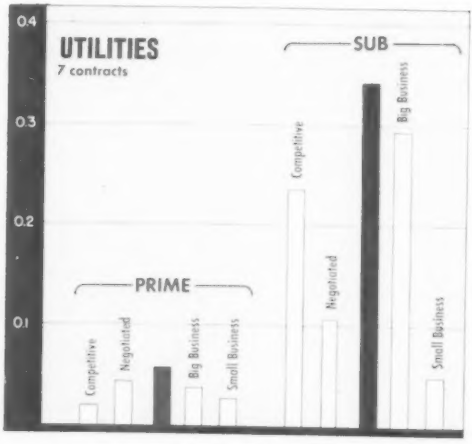

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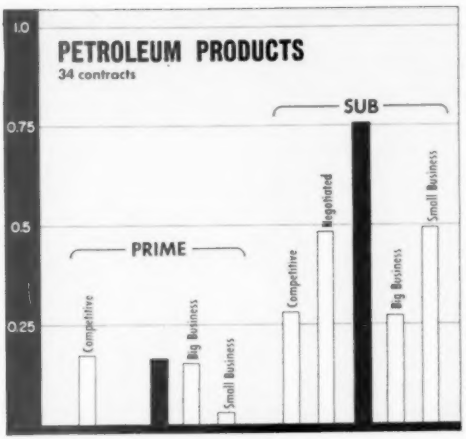

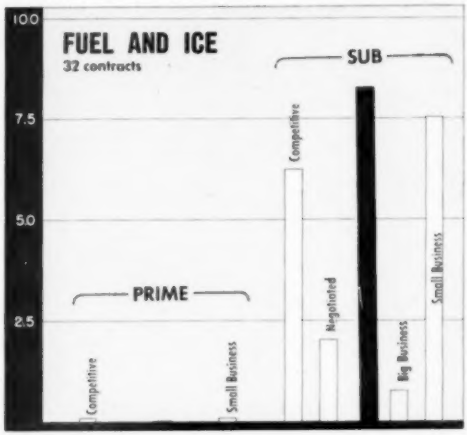

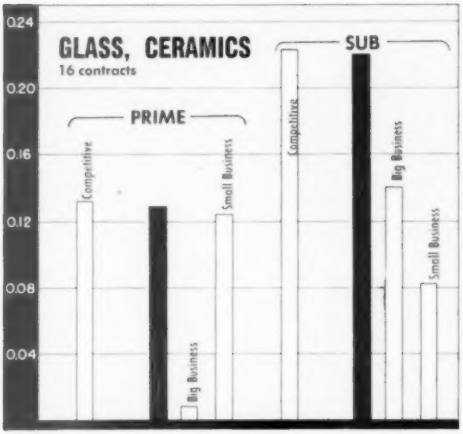

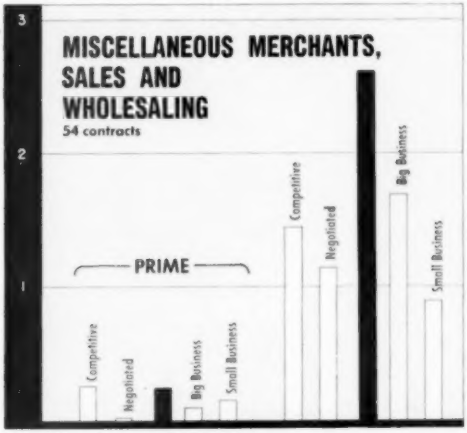

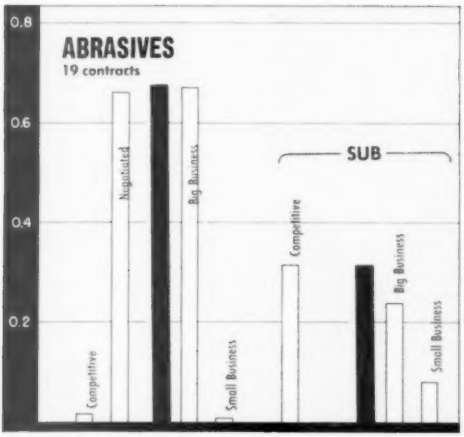

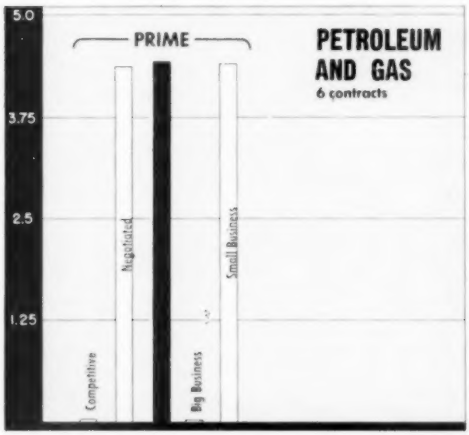

The Future

From the story told on the previous pages, it is apparent that atomic energy already is big business. The question now is: where do we go from here? Once again we must talk about two things—the Government's atomic energy program and industry's own. The first is big now and is getting bigger; the second is small now and is just beginning to grow.

The AEC is still in the midst of carrying out its largest expansion to date. Despite this, it already has done considerable planning and thinking about another expansion which would increase the size of the project at least 150% beyond what it will be at the end of the present expansion. Recommendations for a 300–500% increase in appropriations have already been made to Congress. If they are approved, work will get under way some time in 1952.

To gage the effect of this expansion one need merely multiply the figures on the previous pages by some appropriate factor—perhaps anything from 1.5 to 3 or 4. Already, thousands of companies have been involved in the program in one way or another. Further expansion will mean that many more companies will, of necessity, work on the program.

This brings us to the second part of our look into the future. What is there in this field for industry? Thus far, aside from construction and operation, there have been only two things: (1) manufacture and sale of instruments and other products to Government, hospitals, universities and industry, and (2) use of radioactive materials in basic and applied research and in improvement of products and processes.

These activities will grow as the Government's program grows. As more companies gain experience in using and handling radioactive materials, applications of these materials will consequently expand. But the biggest growth will be in reactor technology.

How to Get into Atomic Energy Work

Although mystery and secrecy surround the atomic energy program, thousands of companies have broken through this veil and are working in the field. Actually the awe and fear which many nonparticipating companies have of atomic energy are unwarranted. The program is growing rapidly and many more companies are needed in it. The AEC has announced an "open door" policy to industry. Here is how to take advantage of it:

Q. What companies are eligible to work in the Government's atomic energy program?

A. Almost any type of industrial firm. For large specialized projects, a specific type of experience may be required. But many of the industrial services and products sold to the AEC are those routinely sold by industry.

Q. What should a company do to find out if there is business for it in the atomic energy program?

A. Inquire at the nearest Operations Office of the AEC. For specialized contracts, AEC examines the qualifications of many companies. Therefore it is imperative that AEC be aware of the abilities of interested concerns. Frequently one can learn about equipment and supply needs and about special engineering problems by contacting an Operations Office.

Q. What about secrecy? Is it an insurmountable barrier for uncleared companies wanting to work in the program?

A. Secrecy is a hindrance to over-all progress in the atomic energy field, but it is not much more than a nuisance to an individual company working in the field. If there is the possibility that the AEC might be interested in contracting with an uncleared company to do classified work, the AEC can arrange for clearance for company officials to carry out preliminary classified discussions. This is done quite frequently.

Q. What opportunities are there for a company to do atomic energy work in its own industry, apart from the Government program?

A. There are two possibilities—work with, or related to, radioisotopes, and nuclear reactor technology. Many companies are already putting radioactive materials to use in their own work. In the case of reactors, industry is just beginning to scratch the surface on nuclear power possibilities.

Q. How can a company train personnel for work in the atomic energy field?

A. There are three ways: (1) Send a man to Oak Ridge to take a four-week course in radioisotope techniques given by the Oak Ridge Institute of Nuclear Studies. The fee is nominal. (2) Send a man to the Oak Ridge School of Reactor Technology (conducted by Oak Ridge National Laboratory) to take a one-year course in all aspects of reactor technology. (3) Train employees in laboratories operated by certain AEC contractors. The AEC endorses special arrangements made by contractors, such as (a) Argonne National Laboratory, where industry employees are assigned to work for one or two years; (b) another covered by a clause is the AEC contract with GE, permitting other companies to send their employees to work (up to a total of 15, or 5% of the technical staff) at the Knolls Atomic Power Laboratory. A number of companies have already taken advantage of this opportunity to gain invaluable experience.

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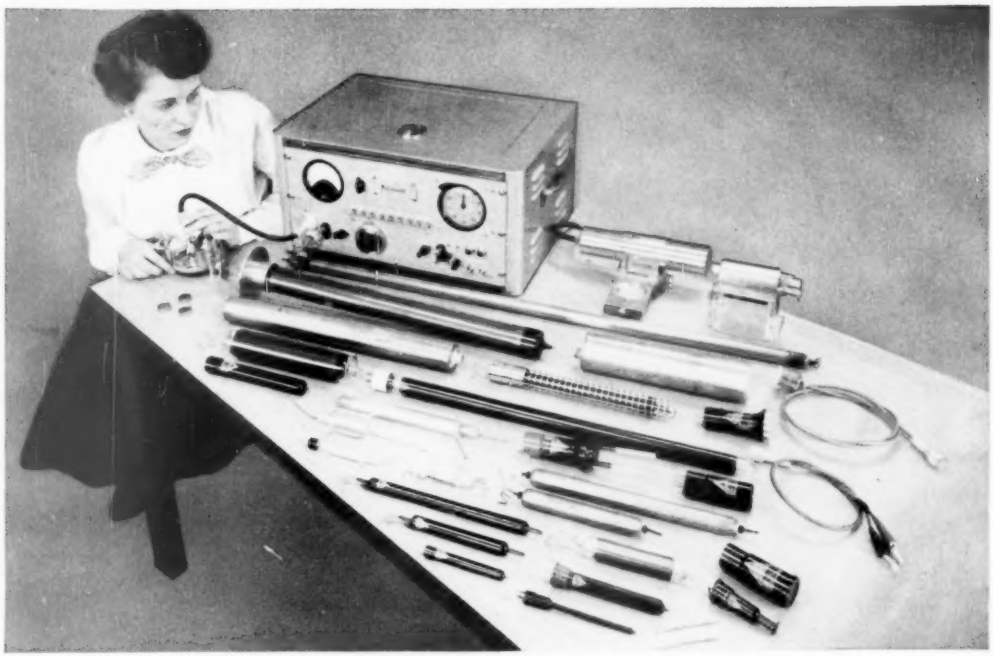

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